Resources Flow and Its Environmental Impacts

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Abstract: In the 21st century, China is facing some challenges, e.g. population growth, rapid economy development, resources limitation and environmental vulnerability. Resource-use efficiency and the environmental impacts associated with growing resource utilization is a new challenge for both scientists and politicians, especially. In this paper, the concepts of resources and resource products flow is presented in order to analyze the environmental impacts that occur as a result of the resource flow process. We focus on forest resources, coal products and oil flows as these the main resources and products that are produced continuous severe and increasing environmental pressure. The data for domestic yield and exploitation, importation, exportation, and consumption, for various industries come from China’s forest statistical yearbooks for the period 1949 to 2001, and China’s energy statistical yearbooks for 1980 to 2006. We divided the resources flow process into key stages, such as harvest, exploitation, process or conversion and end consumption. Resources efficiency and environmental performance for each stage were evaluated. This study showed: resource-use efficiency improved and the structure of resources consumption has been optimized markedly in the past decades in China. However, the absolute quantities of resources consumption are still increasing, and the environment pressures originating from resource use became more severe.

Key words: resources flow; environmental impacts; forest; coal; raw oil

1 Introduction

Because it provides the information necessary to support well-informed decisions (Adriansse et al. 1997; CEQ and OSTP 1998; Hinterberger et al. 1997; Sundkvist et al. 1999), a comprehensive analysis of resource flows, utilization efficiency, and the associated environmental impacts in a given socioeconomic system is an important part of developing and implementing resource management strategies.

Resource-flow analysis (RFA) is a systematic methodology that can be used for tracking the flow of materials throughout a country, region, city, or organization. The outcomes of a resource-flow analysis improve our understanding of how and where to target activities designed to manage material consumption while minimizing any associated negative impacts (Chambers et al. 2005). RFA is an effective tool for evaluating the sustainability of resource use and environment. Economy and environment are closely connected through material and energy flows, from which many environmental problems can result (Scasny et al. 2003). Reducing material inputs is an alternative management strategy for sustainability (Hinterberger et al. 1997).

Several methods are used for RFA. Material-flow analysis (MFA) reveals hidden or unexpected flows and emissions, as well as the accumulation of stocks of a resource or a pollutant in an economy or the environment, providing warnings of potential future problems and opportunities (Binder et al. 2004). MFA can be used to examine the materials throughput or intensity of national economies, important economic sectors, or large functional systems by tracking mass flows through the whole system (Bouman et al. 2000). The life-cycle assessment (LCA) meth-
odology has also proved to be a valuable tool for documenting and analyzing the environmental aspects of product and service systems at all stages in the life cycle of a resource, and is an important part of decision-making process (Hellweg 2005). LCA is widely used in resource-flow analysis because it traces the flows from the initial extraction of raw materials to processing, trading, and consumption of the products or services created using those materials, and concludes with analysis of treatment of the wastes produced when a product or service reaches the end of its service life and can no longer be used (Tan and Khoo 2005).

In the past 50 years, Chinese scientists organized by Chinese Academy of Sciences, have completed a series of field survey projects of natural resources which provide a solid scientific data base for decision-making for resources development. Chinese scientists have also carried out numerous successful strategic projects. However, natural resources flow processes have been largely ignored, and this is exceedingly urgent and important for a recycle economy and future sustainable development. Thus, decision-makers and researchers lack a comprehensive understanding of natural resource flows and their economic and environmental effects. China faces a serious shortage of natural resources, which will lead to serious conflicts between the demand for these resources, and the need to protect the country’s fragile natural environment. Fossil energy and fuel resources and agricultural products constitute the major resource products flow in China. Based on natural resources harvesting and resource processing data for the past 50 years, we develop a general framework for resource-flow analysis (Fig.1), and use it to perform an overall analysis of China’s resources flow. This framework reveals the changing characteristics of resources flow and provides a scientific basis that can provide support for the decisions made by decision-makers.

The framework of Resources-flow analysis (RFA) includes: (i) Tracing the spatiotemporal dynamic process of RF among regions and industries. Analyze the process of resources flow among various industries in different regions, e.g. where do the resources come from? Where do they go? How are they used in industries? (ii) Analyzing the driving forces and mechanisms of RF. Generally, resources/products scarcity, difference in quality, and uneven distribution across regions can increase the flow of resources/products across regions and industries; (iii) Identifying economic, social, and environmental effects during the process and crucial stages of RF. Identifying problem sections and problem regions. Ascertaining who are responsible for resource efficiency and environmental impacts. (iv) Establishing regulations for resources use, environmental protection, population growth, urbanization, etc.

2 Methodology and data

Based on the rule of material balance, for a specific middle-product generated in the flow process (Fig. 2), the relationship between input and output is as follows:

\[ \text{DRI} + \text{I} = \text{DPO} + \text{E} \]

Where: DRI= Domestic Resource Input; DPO= Domestic Product Output; I= import; E= export.

Environment Impacts (EI) in resource flow can be calculated as the quantity of resources flow (RF) multiplied by the Coefficient of Environmental Impact (CEI).

\[ \text{EI} = \text{RF} \cdot \text{CEI} \]

Domestic forest production and import-export volume of fuelwood, logs, saw timber, wood-board, veneer, fiber board, pulp, etc. are from China’s forest statistical yearbooks for 1953–2000. We converted physical volumes into a uniform measurement of log equivalency with the production coefficient for forest resources consumption. Annual data for fossil energy resources and products, including coal and oil, were available from the National Energy Balance of “China Energy Statistical Yearbooks” for the period 1980 to 2006. In order to facilitate comparison
and tracking the process, a unified unit, i.e. 10,000 tonnes coal equivalent (tce) is selected to measure the flow of coal and oil. With the conversion coefficient, the physical quantity of all resources/products can be converted into standard quantity, such as tonne of coal equivalent.

3 Case study

3.1 Forest resources and products flow

Using the analysis framework of RFA, three characteristic of forest/products flow in China can be deduced, a) China’s forest resources flow shows a rapid increase tendency; b) the structure of forest resource use has improved; c) the environmental implication of forest resources use continues to be severe.

From the 1st FYP to the 9th FYP (1953–2000), China’s forest resources flow showed an accelerating tendency to increase (Figs. 3 and 4). The Total Material Requirement (TMR = CA + DRI + NIR + NIP) of forest products increased from 33.85 million cubic meters to 137.19 million cubic meters (Fig. 5).

The Total Net Import (TNI = NIR + NIP) of forest resources and products from overseas is also increasing. This implies that China is an increased tendency towards consumption that depends on the import of forest resources from the overseas markets.

The structure of forest resource use has been improved to a certain degree (Fig. 6). During the early 1980s, China’s forest resources were mainly used in the log and saw-timber processing industry. With advancing technology and changing market demand, more and more forest resources flowed into the artificial wood-board and paper-making industries during the 9th FYP (1996–2000).

During the 6th FYP (1981–1985), imported forest resources were dominated by raw materials such as logs and pulp. While During the 9th FYP, the import of finished products such as paper increased dramatically.

Fig. 3 Forest resource and product flows in China from 1953 to 1957.

Fig. 4 Forest resources and product flows in China from 1996 to 2000.
Environmental impacts from forest resources use continue to be severe. Reuse of forest resources waste/remains has increased and the amount of combusted and forest resource wastes has declined greatly. Efficiency of forest resources utilization has continued to increase over the past 47 years. However, the absolute increases in forest resource consumption have negative effects on the fragile environment.

Forest resources management measures in China lie in (i) the reduction of forest resources flow in different industries and across different regions; (ii) the promotion of structural readjustments in forest industry; and (iii) making full use of forest resources imported from overseas markets, to lower dependence on external forest resources.

3.2 Coal and products flow

Generally, there are four basic conversion processes for changing raw coal into coal products, i.e., coal washing, briquetting, coking and gasification. The raw coal and the coal products such as washed coal, briquette, coke and oven gas are consumed at the middle and end consumption levels. The middle consumption level includes the four conversion process and thermal power and heating, and end consumption includes agriculture, industry, commerce, transportation, construction and residential building. Fig. 7 and Fig.8 show coal flow in China from 1991 to 2005.

The main middle consumption level for raw coal use in...
includes washing, coking, thermal power, and the heating, and the main final consumption level includes industrial and agricultural use. The washed coal products were used for nearly all the middle and end coal consumption levels.

The coking products were mainly consumed in industry. The share of raw coal in the total coal and products consumption decreased for the period from 1991 to 2005. Fig. 9 showed the end consumption composition in China in this period.

The average growth rate of raw coal production reached 5.2% annually in the period from 1991 to 2005 (Fig. 10), while the production of coal products such as cleaned coal, coke and gas increased more distinctively. For example, the increasing rate of briquettes use reached 37.9% annually from 1991 to 2005. The increasing demand from home and overseas, increased the production of coking products, the average growth rate being more than 10% for the period.

Table 1 Coefficients of Environmental Impacts (CEI) of coal exploiting and consumption.

<table>
<thead>
<tr>
<th>Environmental impacts</th>
<th>CEI</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exploitation</td>
<td>Land subsidence</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Gangue dump</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Acid mine drainage</td>
<td>6.10</td>
</tr>
<tr>
<td>Combustion</td>
<td>CO₂ emission</td>
<td>2.37</td>
</tr>
<tr>
<td></td>
<td>SO₂ emission</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>TSP emission</td>
<td>0.05</td>
</tr>
<tr>
<td>Coking</td>
<td>COD₅</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Ammonia</td>
<td>0.05</td>
</tr>
<tr>
<td>Gas Works</td>
<td>waste water drainage</td>
<td>1.12</td>
</tr>
</tbody>
</table>
processing. The ecology effects and environment pollution that are caused by the processes involved can be very severe. Thus, the flow of coal and coal products to overseas importers are damaging China's environment and ecology.

Scientific and technological innovation is gradually improving the ratio of output/input for the washed coal, briquettes, coke and oven gas. Mineral content in raw coal increases transportation costs and damages environment during the process of combustion, coking and gasification. The proportion of coal prepared in total raw coal has increased, from 68.5% in 1991 to 95.6% in 2005. The yielding ratio of coking and gasification improved steadily in the past 15 years also.

A total of 84% of coal production in China is combusted directly. As much as 90% of SO₂ emission and the 70% of solid particle come from coal combustion (Gu and Wang 2009). The Coefficients of Environment Impacts (CEI) in the stage of exploitation and combustion is derived from Ju et al. (2006), and the CEI in coking and gasworks is from Gu and Wang (2009) (Table 1).

Environment impacts associated with the coal exploitation, processing and consumption are both significant and very serious. Taking into account that china's large population must be fed, together with the vulnerability of the environment and ecology, and the fact that greenhouse gas (GHG) emission need to be reduced, China is faced with problems of dependency on the current coal-based energy mix.

In China, land subsidence associated with coal exploitation rose to 44 095 hectare in 2005 (Table 2), and the accumulated land subsidence in coal mining areas had reached over 400 000 hectare by 2005. Gangue discharge and acid mine drainage have all increased over the past 15 years. In particular, the GHG emission including CO₂, SO₂ have doubled over the past 15 years. Chemical material such as COD and ammonia and the wastewater from coking process and gasworks rose tremendously in this same period.

### 3.3 Oil and petroleum flow

The oil resources/products can be grouped into eight categories, including crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas (LPG), refinery gas and other petroleum products. We analyzed the extraction, refining and consumption of oil resources flow and constructed flow diagrams for the period 1980 to 2006 (Figs. 12 and 13).

From 1980 to 2006, domestic oil extraction had increased continually, with annual growth rates of 10.63%. Crude oil production was diversified for various regions. By 2006, 24 crude oil production bases had been estab-

<table>
<thead>
<tr>
<th>Year</th>
<th>Land subsidence (ha)</th>
<th>Gangue discharge (10⁴ t)</th>
<th>Acid mine drainage (10⁴ t)</th>
<th>CO₂ (10⁴ t)</th>
<th>SO₂ (10⁴ t)</th>
<th>TSP (10⁴ t)</th>
<th>COD₄ (10⁴ t)</th>
<th>Ammonia (10⁴ t)</th>
<th>Waste water (10⁴ m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>21 748</td>
<td>14 136</td>
<td>474 109</td>
<td>183 772</td>
<td>2120</td>
<td>3915</td>
<td>4899</td>
<td>87</td>
<td>108 859</td>
</tr>
<tr>
<td>1995</td>
<td>27 215</td>
<td>17 690</td>
<td>593 279</td>
<td>229 964</td>
<td>2653</td>
<td>4899</td>
<td>87</td>
<td>7</td>
<td>108 859</td>
</tr>
<tr>
<td>2000</td>
<td>19 960</td>
<td>12 974</td>
<td>435 128</td>
<td>168 662</td>
<td>1946</td>
<td>3593</td>
<td>74</td>
<td>6</td>
<td>79 840</td>
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<tr>
<td>2005</td>
<td>44 095</td>
<td>28 662</td>
<td>961 262</td>
<td>372 599</td>
<td>4299</td>
<td>7937</td>
<td>158</td>
<td>12</td>
<td>176 378</td>
</tr>
</tbody>
</table>

Table 2 The environmental impacts associated with the coal use and coal flow.
The oil refining process is characterized by: (i) The flow to the refining sectors rapidly increased and the refinery capacities have been markedly improved. From 1980 to 2006, refinery capacity grew by 10.19% annually, i.e., much higher than the world average. In 2006, China became the second largest oil refining country, second only to the United States. (ii) The domestic supply of oil products increased significantly, from 240 million tce to 690 million tce, at an annual growth rate of 6.58%. Diesel oil and gasoline were the fastest growing products (Fig.14). (iii) The flow composition gradually improved and secondary processing capacity increased significantly.
Throughout the study period, the proportion of oil products declined from 72.02% in 1980 to 67.58%. There was a gradual transfer to fuel-chemical production. The yield of light oil products, including gasoline, kerosene, diesel and LPG showed a rising trend, and its share increased continually from 55.25% in 1980 to 75.72% in 2006 (Fig. 15).

Transportation industry has represented a major consumer of oil products with the domestic automobile industry being the main driving force for gasoline and diesel consumption. Kerosene is mainly used in the rapid development of air transport. Being a clean energy form, LPG was usually used as a cooking fuel, and as vehicle fuel.

Fig. 13 The oil flow in China in 2006, unit: 10 000tce

Fig. 14 Output of domestic oil products (1980–2006).
As the structure of consumption developed towards lighter fuels, the proportion of light oil gradually increased. Fig. 16 is the structure of oil consumption for the period 1980–2006. The inflow of foreign crude oil rapidly increased and external dependency showed rise. In 2006, the China's net import of crude oil reached 207 million tce, and dependency on imported crude oil reached 42.9%. Fuel oil constituted the largest imported refined oil (Fig. 17), with LPG in second place.

With further developments in technology and management, the rate of loss in the refining processing showed a decreasing trend, from 2.85% in 1980 to 0.62% in 2006. The growth in resources efficiency and improvements in oil production technology, together with better consumption structures, all benefitted the environment and ecology.

4 Discussion

From the resources flow research, especially the three case studies for resources and products flow of forest, coal and oil products, some conclusions can be drawn: (i) resource-use efficiency improved and the structure of resources consumption has been optimized markedly in the past years. However, the absolute quantities of resources consumption are still increasing, so the environment pressures originating from resource use and consumption have become more severe. (ii) A number of measures can be applied for resources management in China: a) from the point of view of end use in resources flow, a reduction in the demand for the resources is the most effective method to improve resource-use efficiency and to protect environment. It will be necessary to advocate strategy for resources saving in China by introduction of some specific regulations. b) From the middle process in the resources flow cycle, the residues emitted at the middle stage should be recycled with the ideas and methodology of an industrial ecosystem. c) The industrial structure should be adjusted and resources should be allocated rationally. Resources should be allocated preferentially to those processes that have high levels of efficiency and which are environmentally friendly.

Resources flow research is an initiative with a new angle to consideration by the natural resources sciences. The clearer we reveal the flow process of the resources, the clearer we can understand the relationships between the resources and the environment, the more solid base we will have to advise on and put forward suggestions to policy-makers. The flow processes and their impacts are of significance for resources flow research in China. Resources Flow Analysis is a new tool by which to analyze the resources and products flow together with the associated environmental problems. However, there are some limitations to this analysis framework. A reasonable model to simulate the flow process of resources and their products is urgently needed. The input-output analysis and the Computable General Equilibrium model should be applied in the allocation of resources in the socioeconomic process. In additional, the accessibility to data is a huge obstacle in resources flow research. Nothing can be achieved without access to reliable data. Data for resources and their products need to be compiled in order to build an effective database that will help forward resources flow research. This is a challenging task for the near future.
资源流动的环境效应

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摘要：21世纪，中国的人口和经济的持续增长面临着资源短缺和生态脆弱的限制。提高资源利用效率和消减资源利用引起的环境影响是学术界和决策者面临的新课题。本文从资源流动的视角研究资源利用过程及其引起的环境影响。我们选取了林木、煤炭和石油研究其资源流动过程及环境影响。研究发现，林木产品的产量、进出口量和消费量来自中国森林资源流量年鉴(1949–2001)。煤炭、石油的开采量、进出口量和消费量来自中国能源统计年鉴(1980–2006)。研究表明：过去几十年，中国的资源利用效率有所提高，资源消费结构逐步改善，但资源消费总量居高不下，对生态环境构成极大的压力。

关键词：资源流动; 环境效应; 林木资源; 煤炭; 石油