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Unintended Environmental Consequences and Co-benefits of Economic Restructuring

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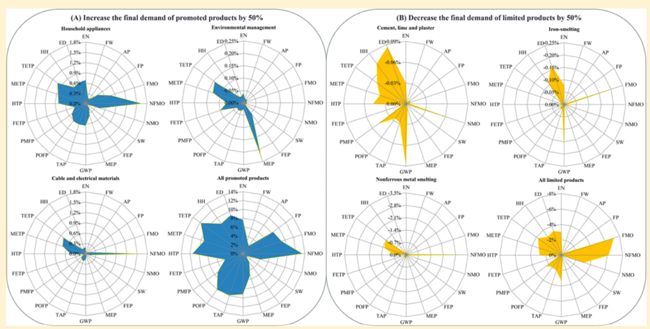
Ⓢ *Supporting Information*

ABSTRACT: Current economic restructuring policies have ignored unintended environmental consequences and cobenefits, the understanding of which can provide foundations for effective policy decisions for green economy transformation. Using the input-output life cycle assessment model and taking China as an example, we find that household consumption, fixed capital formation, and export are main drivers to China's environmental impacts. At the product scale, major contributors to environmental impacts vary across different types of impacts. Stimulating the development of seven strategic emerging industries will cause unintended consequences, such as increasing nonferrous metal ore usage, terrestrial acidification, photochemical oxidant formation, human toxicity, and terrestrial ecotoxicity. Limiting the surplus outputs in the construction materials industry and metallurgy industry may only help mitigate some of the environmental impacts caused by China's regulated pollutants, with little effect on reducing other impacts, such as marine eutrophication, terrestrial acidification, photochemical oxidant formation, and particulate matter formation. However, it will bring cobenefits by simultaneously reducing mineral ore usage, human toxicity, marine ecotoxicity, and terrestrial ecotoxicity. Sustainable materials management and integrated policy modeling are possible ways for policy-making to avoid unintended consequences and effectively utilize cobenefits.



1. INTRODUCTION

An economy interacts with the environment through various material flows[1] which are regarded as the environmental pressure of the economy.[1,2] The flows of materials can cause various types of environmental impacts to the environment.[3,4] Decoupling economic growth from the increase of environmental pressure is regarded as an important way to achieve sustainability.[5] For example, the United Nations encourages countries to take policy measures for the "green economy", one important component being decoupling.[6] Effectively achieving decoupling requires rational policy measures to ensure that unexpected adverse impacts are minimized.

Considering only direct impacts of a particular goods may increase impacts on the whole economy through supply chain linkages.[7] Life cycle assessment (LCA) of products is hence increasingly used to support policy decisions by anticipating indirect effects.[8−10] Moreover, focusing on limited impacts of products may induce problem-shifting.[11−13] Thus, effective policy-making requires considering a wider range of environmental impacts on a life cycle basis. Unintended environmental consequences and cobenefits need to be understood for effective policy suggestions.

China plays a crucial role in the world, due to its size, rapid economic growth, and increasing environmental pressure.[14,15] In order to sustain economic growth while mitigating material flows, the Chinese government has proposed policies to restructure the economy. For instance, China is encouraging the development of seven strategic emerging industries including energy-saving and environmental protection, new-generation information technology, biotechnology, high-end equipment manufacturing, new energy sources, advanced materials, and new fuel vehicles.[16,17] Surplus production of metallurgy and construction materials is also to be limited.

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Table 1. Data Sources for China's Material Flows Inventories in 2007

	material flows inventories	data sources
resources	energy	*China Energy Statistical Yearbook 2008*[39]
	freshwater	*2007 Annual Statistic Report on Environment in China*[40] water usage of service sectors is estimated based on some assumptions.[22,34,41]
	agricultural products forestry products ferrous metal ores nonferrous metal ores nonmetallic ores	*China Agriculture Yearbook 2008*[42] *China Mining Yearbook 2008*[43] their aggregated domestic consumption data are decomposed using the proportionate relationships of monetary intermediate allocation data of related rows in Chinese 2007 MIOT.
pollutants	water pollutants conventional air pollutants conventional solid wastes	*2007 Annual Statistic Report on Environment in China*[40] *Reports on the first nationwide survey of polluters*[44]
	greenhouse gases atmospheric heavy metals	multiplying energy usage and product yields with emission factors[31,36−38]
	crop straws; animal manure; and construction wastes	using existing calculation methods[45,46]

Scholars have evaluated life cycle environmental impacts of Chinese products to provide guidance for the economic restructuring.[9,18,19] There are mainly two limitations in previous studies: (1) unintended environmental consequences and cobenefits caused by China's possible economic restructuring has seldom been studied from a systems perspective. Considering a wide range of environmental impacts to identify unintended environmental consequences and cobenefits can provide additional information for efficient policy-making. (2) The results are given at a low sectoral resolution due to method and data limitations.

This study fills in these gaps by using the Chinese 2007 monetary input-output table (MIOT) in a 135-sector format and considering 20 categories of environmental impacts from the inventory of 49 types of material flows. By considering a wide range of environmental impacts from the life cycle perspective, we identify unintended environmental consequences and cobenefits arising from China's possible economic restructuring to provide insights for policy decisions.

2. METHODOLOGY AND DATA

2.1. Input-Output Life Cycle Assessment Model. Input-output life cycle assessment (IO-LCA) model provides a systematic "top-down" perspective to examine the life cycle impacts of goods by extending the system boundary of conventional process-based LCA.[9,10,20−24] The IO-LCA model treats various types of environmental impacts as physical multipliers of the MIOT. Let the $m \times n$ matrix P represent the intensity of each sector's physical multipliers per unit of its total output, where m and n respectively represent the numbers of physical multipliers and economic sectors. In addition, define the $n \times 1$ column vector y as final demands in each sector. The quantity of each sector's life cycle environmental impacts T, which is an $m \times n$ matrix, is then calculated by eq 1.

$$\mathrm{T} = \mathrm{P}(\mathrm{I} - \mathrm{A})^{-1}\hat{y} \quad (1)$$

The $n \times n$ matrix $(\text{I-A})^{-1}$ is the *Leontief Inverse Matrix*.[25] The notation "^" diagonalizes the corresponding column vector. The $m \times n$ matrix P(I-A)^{-1} indicates each sector's life cycle environmental impact intensity, meaning the direct and indirect environmental impacts of the unitary final demand in each sector.

Environmental impacts in this study are defined as impacts caused by material flows including resource usages and pollutant emissions. Each sector's impacts caused by resource usages are calculated using material flow accounting methods.[1,2] Impacts caused by pollutant emissions are computed by multiplying pollutant emissions with corresponding ReCiPe characterization factors [3] from the hierarchist perspective, which is based on the most common policy principles with regard to time frame and other issues,[26] as shown in eq 2. The main aim of this study is to investigate potential unintended consequences and cobenefits if we take a wide range of environmental impacts into consideration. Thus, we do not mainly focus on how to quantify environmental impacts, but calculate environmental impacts according to currently accepted methods.

$$\mathrm{E} = \mathrm{FM} \quad (2)$$

where the $m \times n$ matrix E indicates m categories of environmental impacts by n economic sectors; the $m \times k$ matrix F stands for the ReCiPe characterization factors converting k categories of material flows into m categories of environmental impacts; and the $k \times n$ matrix M represents the amounts of k categories of material flows by n economic sectors.

In the ReCiPe methodology for life cycle impact assessment, there are midpoint and end point levels which are different steps of a complete LCA.[26] The midpoint level can be regarded as an intermediate step giving complex results with low uncertainty, while the end point level can be regarded as a final step giving simplified results with high uncertainty.[26] We use both levels in the calculation of this study to provide comprehensive information. We consider 20 categories of environmental impacts in this study including energy usage (EN), freshwater usage (FW), agricultural products usage (AP), forestry products usage (FP), ferrous metal ores usage (FMO), nonferrous metal ores usage (NFMO), nonmetallic ores usage (NMO), solid wastes emissions (SW), freshwater eutrophication (FEP, midpoint), marine eutrophication (MEP, midpoint), climate change (GWP, midpoint), terrestrial acidification (TAP, midpoint), photochemical oxidant formation (POFP, midpoint), particulate matter formation (PMFP, midpoint), freshwater ecotoxicity (FETP, midpoint), human toxicity (HTP, midpoint), marine ecotoxicity (METP, midpoint), terrestrial ecotoxicity (TETP, midpoint), human health damage (HH, end point, measured by disability-adjusted loss of life years), and ecosystem diversity damage (ED, end point, measured by the loss of species during a year).

2.2. Data Sources. Two types of data are needed for the IO-LCA model: the Chinese MIOT and material flows inventories at the sectoral scale. We use China's 2007 commodity-by-commodity MIOT in the 135-sector format (Supporting Information, SI, Table S1).[27] Each sector represents production activity of a particular category of products. We also remove the "others" column regarded as the error of different statistical sources.[11,12,28−31] Focusing on life

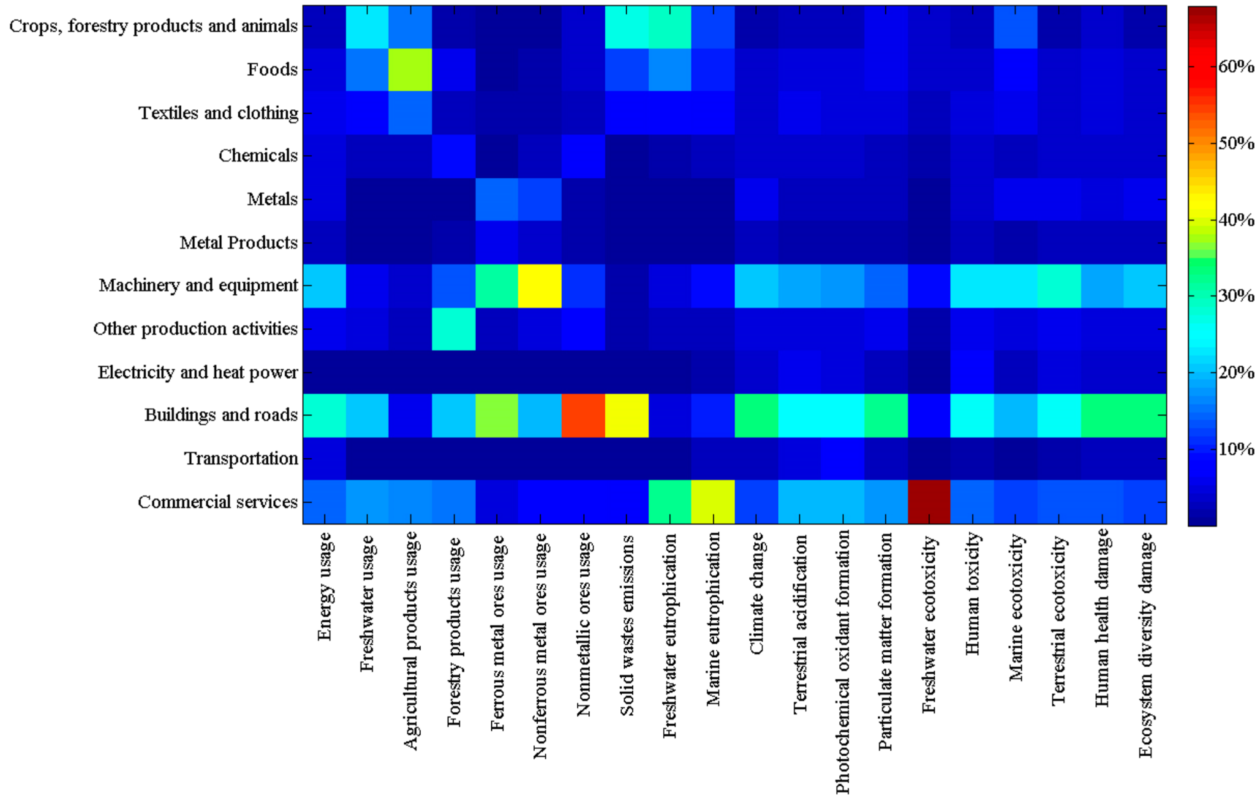

Figure 1. Life cycle environmental impacts of Chinese goods and services.

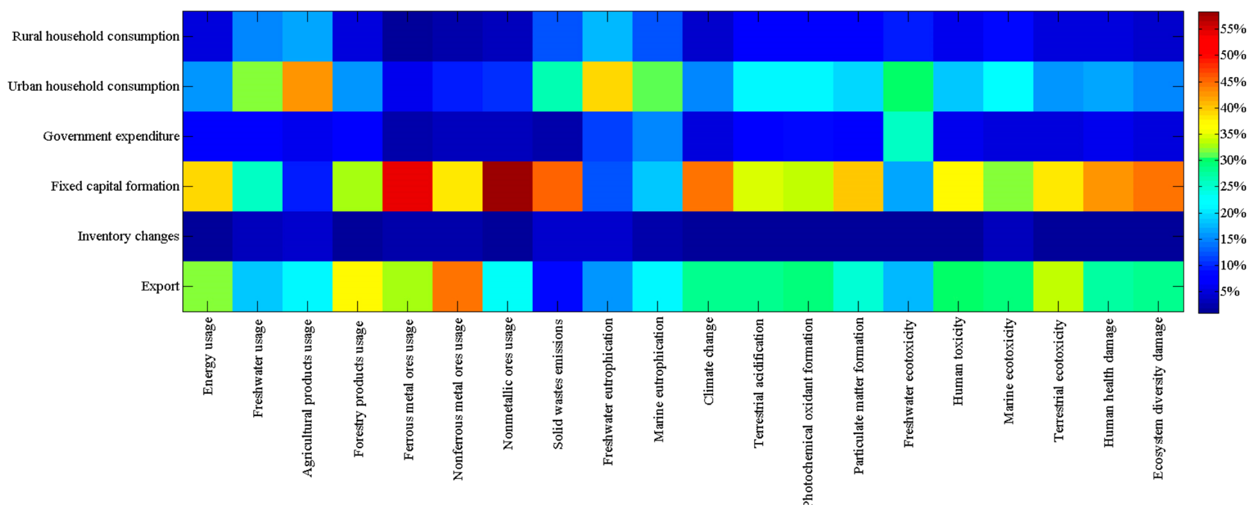

Figure 2. China's environmental impacts by final demands.

cycle environmental impacts induced by domestic economic activities, we remove imports from the standard Chinese 2007 MIOT using existing methods from the literature.[32,33] We also construct material flow inventories in the 135-sector format (Table 1). Forty-nine types of materials are considered, which are then converted into 20 categories of environmental impacts using the ReCiPe characterization factors (SI Table S2).[3] Details about data sources for material flow inventories are provided in the SI.

Chinese environmental statistics are primarily in a 40-sector format. We disaggregate data in the 40-sector format into a 135-sector format based on the Chinese 2007 MIOT. We proportionately disaggregate resources flow data according to related monetary flows in the Chinese 2007 MIOT [31] under the unique sectoral price assumption.[34,35] We use relevant emission factors[31,36−38] to derive the inventories of emissions based on resource usage in each sector and proportionately disaggregate according to related monetary flows in the MIOT if necessary.

3. CHINA'S ENVIRONMENTAL IMPACTS INVENTORIES

3.1. Life Cycle Environmental Impacts of Goods and Services. China's resources usage in 2007 is mainly driven by the consumption of crops, forestry products and animals, foods, metals, machinery and equipment, buildings and roads, and commercial services (Figure 1). Consumption of crops, forestry products and animals, foods, textiles and clothing, machinery

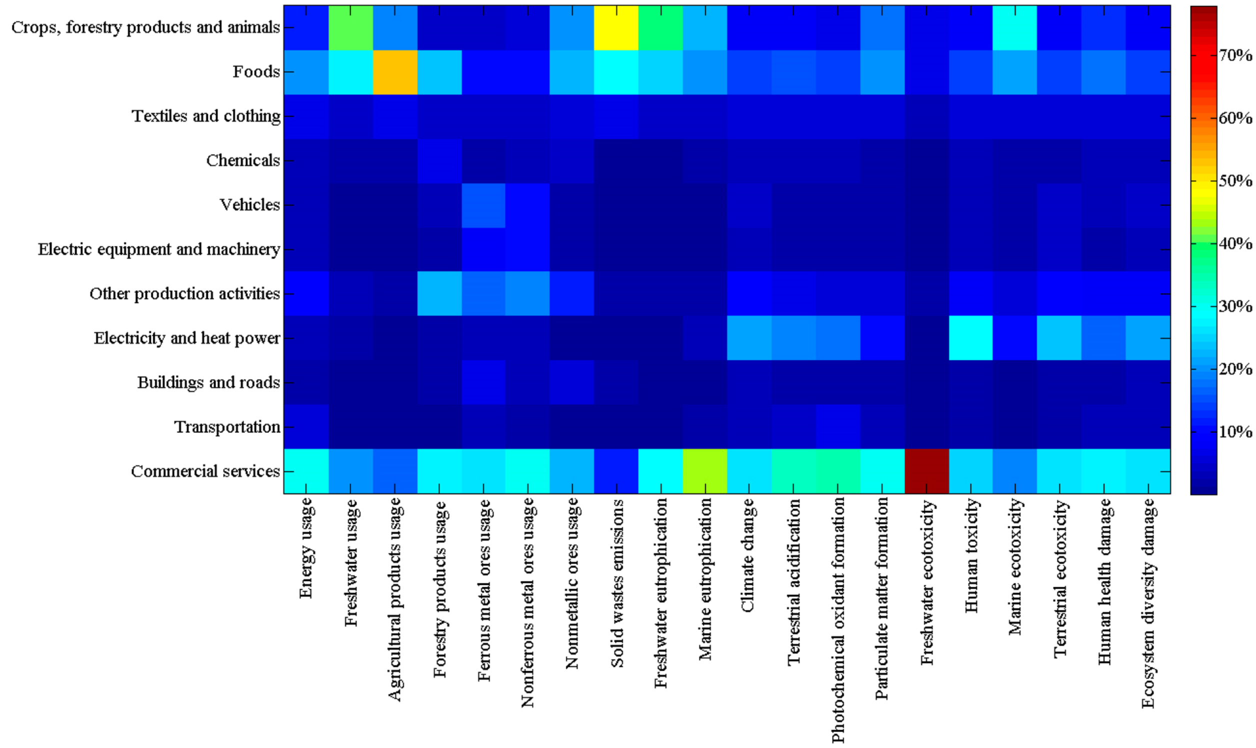

Figure 3. China's household consumption-induced environmental impacts by goods and services.

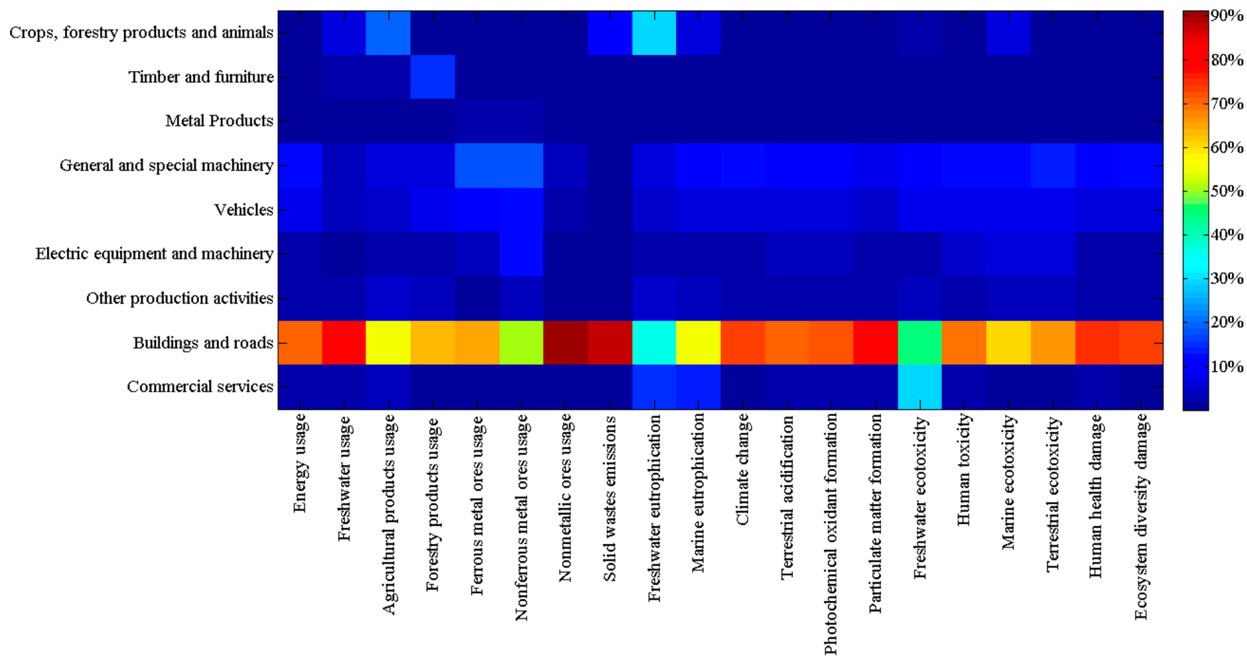

Figure 4. China's environmental impacts caused by fixed capital formation.

and equipment, buildings and roads, and commercial services are main drivers to midpoint environmental impacts, including FEP, MEP, GWP, TAP, POFP, PMFP, FETP, HTP, METP, and TETP. Main drivers to end point environmental impacts (HH and ED) are the consumption of machinery and equipment, buildings and roads, and commercial services.

The consumption of particular goods or services drives environmental impacts in different ways as shown in Figure 1. For example, the consumption for crops, forestry products and animals has limited contribution to mineral ores usage, climate change, terrestrial acidification, and photochemical oxidant formation, but contributes greatly to freshwater usage, solid wastes emissions, and freshwater eutrophication. Moreover, demands for textiles and clothing contribute less to metal ores usage, but greatly to agricultural products usage and freshwater eutrophication. Similar situations exist for other goods and services. This indicates that the consumption of particular goods drives environmental impacts in different ways, which implies environmental problem-shifting as a potential unin-

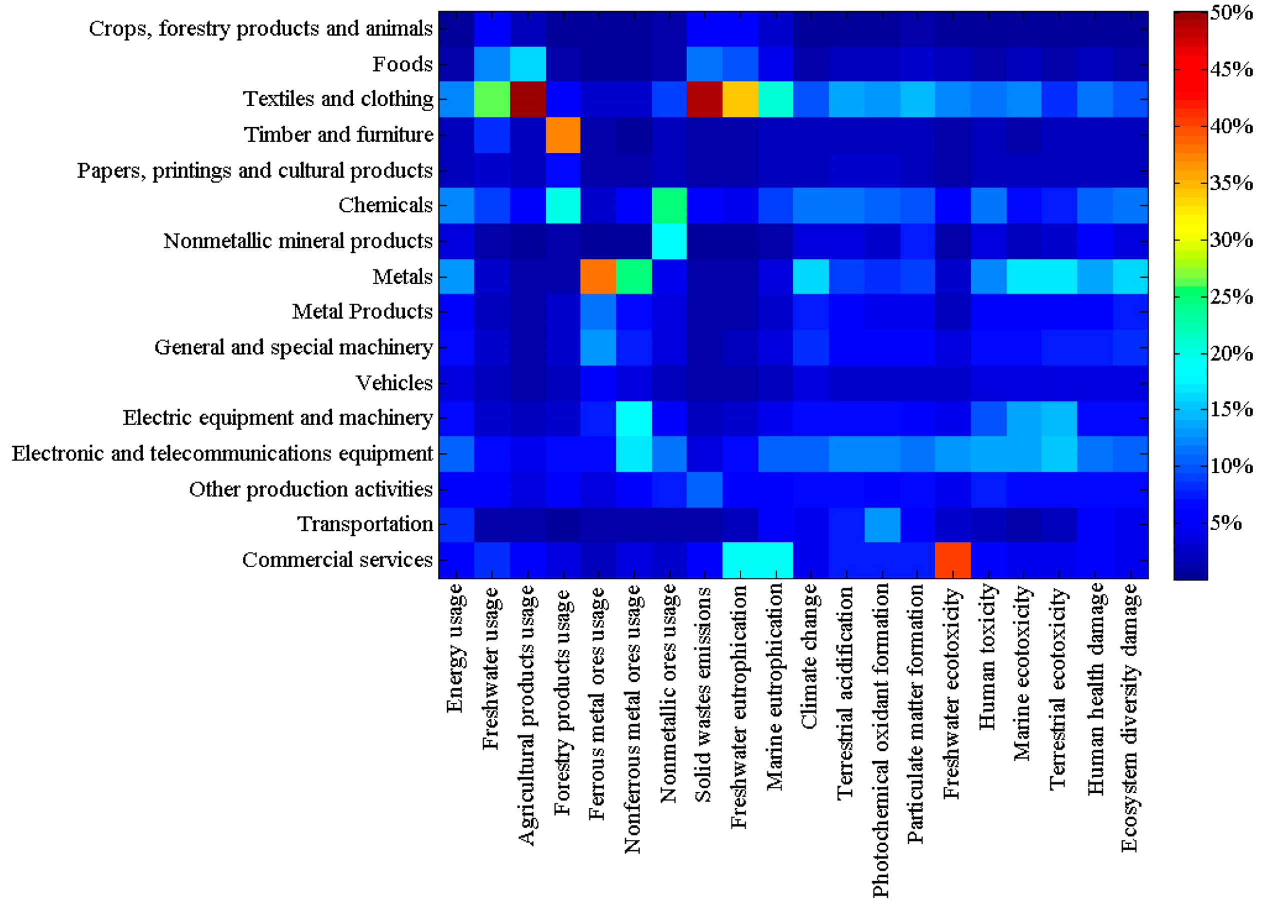

Figure 5. China's environmental impacts caused by exports.

tended consequence of policies targeting at particular industries and/or particular environmental impacts.

3.2. Environmental Impacts by Final Demand Categories. We decompose China's environmental impacts by final demands. As shown in Figure 2, household consumption, fixed capital formation, and exports are main drivers to China's environmental impacts, while they are also China's major economic engines.[47] We further analyze environmental impacts caused by these three types of final demands in the following paragraphs.

3.2.1. Household Consumption. The consumption of crops, forestry products and animals, foods, textiles and clothing, vehicles, electricity and heat power, and commercial services is the main contributor to the household consumption-driven environmental impacts (Figure 3). In particular, the consumption of crops, forestry products and animals by households has marginal contribution to forestry products usage, metal ores usages, climate change, terrestrial acidification, photochemical oxidant formation, freshwater ecotoxicity, human toxicity, terrestrial ecotoxicity, and ecosystem diversity damage, but contributes greatly to the other environmental impacts (Figure 3). Household consumption for vehicles contributes significantly to only the metal ores usages (Figure 3). As shown in Figure 3, the household consumption of electricity and heat power also shows similar patterns on consequential environmental impacts. Focusing on a wider range of environmental impacts, policies promoting green lifestyle can be more efficient to avoid potential unintended environmental problem-shifting.

3.2.2. Fixed Capital Formation. Figure 4 shows that fixed capital formation of crops, forestry products and animals, timber and furniture, general and special machinery, vehicles, electric equipment and machinery, buildings and roads, and commercial services is the main contributor to environmental impacts driven by fixed capital formation. China has been conducting large-scale construction activities to satisfy its rapid industrialization and urbanization demands. Subsequently, fixed capital formation of buildings and roads is the largest contributor to China's comprehensive environmental impacts (Figure 4).

We also find that fixed capital formation of crops, forestry products, and animals has a large contribution to the usage of freshwater and agricultural products as well as solid wastes emissions, freshwater eutrophication, marine eutrophication, and marine ecotoxicity, while it has less contribution to other environmental impacts. Similarly, fixed capital formation of commercial services has significant contribution to freshwater eutrophication, marine eutrophication, and freshwater ecotoxicity, while it contributes marginally to other environmental impacts. There also exist similar situations for the fixed capital formation of timber and furniture, general and special machinery, vehicles, and electric equipment and machinery. It is most likely that China will continue the massive capital investments in sectors such as household appliances manufacturing, transportation services, and commercial services to support its continuous urbanization process and improving residential living standards. Any policies targeting at reducing environmental impacts related to fixed capital formation should

Figure 6. Changes of environmental impacts if increasing the final demands of promoted industries by 50% (A) or decreasing the final demands of limited industries by 50% (B). Abbreviations in radar charts represent the following environmental impacts: energy usage (EN), freshwater usage (FW), agricultural products usage (AP), forestry products usage (FP), ferrous metal ores usage (FMO), nonferrous metal ores usage (NFMO), nonmetallic ores usage (NMO), solid wastes emissions (SW), freshwater eutrophication (FEP, midpoint), marine eutrophication (MEP, midpoint), climate change (GWP, midpoint), terrestrial acidification (TAP, midpoint), photochemical oxidant formation (POFP, midpoint), particulate matter formation (PMFP, midpoint), freshwater ecotoxicity (FETP, midpoint), human toxicity (HTP, midpoint), marine ecotoxicity (METP, midpoint), terrestrial ecotoxicity (TETP, midpoint), human health damage (HH, end point), and ecosystem diversity damage (ED, end point).

pay special attention to potential environmental problem-shifting.

3.2.2. Exports. Environmental impacts induced by China's exports are mainly because of the export of foods, textiles and clothing, timber and furniture, chemicals, nonmetallic mineral ores, metals, metal products, equipment and machinery, and services (Figure 5). The export of textiles and clothing contributes the most to most environmental impacts. On the basis of the consumption-based accounting framework,[48] a large portion of China's environmental impacts is produced to satisfy the consumption needs of textiles and clothing by its trading partners.

Similarly, major contributors to environmental impacts caused by exports vary across different types of environmental impacts (Figure 5). Taking the largest contributor—textiles and clothing—for example, although the export of these goods contributes less significantly to the usage of forestry products, ferrous metal ores, and nonferrous metal ores, it contributes greatly to other environmental impacts. China has been adjusting its export structure in recent years to encourage exporting more high-end products, such as mechanical and electrical equipment, and less energy- and pollution-intensive goods, such as fossil fuels, mineral ores, ferrous metals, and nonferrous metals. Given the potential environmental problem-shifting, China's export structure optimization should consider a wider range of environmental impacts instead of just energy usage and common pollutants such as carbon dioxide, sulfur dioxide, nitrogen oxides, chemical oxygen demand, and ammonia nitrogen as regulated in the five-year plans.

4. CHINA'S ECONOMIC RESTRUCTURING

China is struggling to transform its economic structure to achieve sustainable development in the coming decades. The Chinese government has two main emphases: (1) stimulating the development of seven strategic emerging industries, including energy-saving and environmental protection, new-generation information technology, biotechnology, high-end equipment manufacturing, new energy sources, advanced materials, and new fuel vehicles; and (2) limiting the total capacity of the construction material industry and metallurgy industry to avoid surplus production. We identify products and services that represent these industries (SI Table S3) to understand the impacts of those strategies.

Figure 6 shows that increasing or decreasing the final demand of a particular product or service will have different performances across different environmental impacts. The development of seven strategic emerging industries may cause unintended environmental consequences. For example, increasing the final demands for those seven industries by 50% will increase impacts on nonferrous metal ores usage, terrestrial acidification, photochemical oxidant formation, human toxicity, and terrestrial ecotoxicity by 13.5%, 9.9%, 10.0%, 11.5%, and 11.8%, respectively (Figure 6A).

Reducing the final demands of products representing construction materials industry and metallurgy industry will have significant contribution to mitigating various environmental impacts on energy usage, mineral ores usage, climate change, human toxicity, marine ecotoxicity, terrestrial ecotoxicity, human health damage, and ecosystem diversity damage (Figure 6B). In recent five-year plans, China paid special attentions to reduce the usage of energy and freshwater and emissions of regulated pollutants which mainly correspond to impacts on climate change, marine eutrophication, terrestrial acidification, photochemical oxidant formation, particulate matter formation, human health damage, and ecosystem diversity damage.[3] As shown in Figure 6B, limiting the final demands for construction materials and metals will have relatively large effects on reducing energy usage, climate change, human health damage, and ecosystem diversity damage, but limited effects on reducing marine eutrophication, terrestrial acidification, photochemical oxidant formation, and particulate matter formation. Taking iron-smelting for example (Figure 6B), decreasing its final demand by 50% will have relatively large effects on reducing ferrous metal ores usage (0.2%), climate change (0.2%), and ecosystem diversity damage (0.2%), but only marginal effects on other environmental impacts. Likewise, decreasing the final demands for the construction material industry and metallurgy industry by 50% will reduce energy usage (3.0%), ferrous metal ores usage (7.2%), nonferrous metal ores usage (6.2%), nonmetallic ores usage (3.1%), climate change (3.3%), human toxicity (2.8%), marine ecotoxicity (3.1%), terrestrial ecotoxicity (3.7%), human health damage (3.0%), and ecosystem diversity damage (3.3%), but have relatively limited effects on reducing other environmental impacts (Figure 6B). In addition to helping mitigate parts of environmental impacts caused by China's regulated resources and pollutants, limiting the development of those industries will lead to significant cobenefits by simultaneously reducing mineral ores usages, human toxicity, marine ecotoxicity, and terrestrial ecotoxicity.

If the final demands of all promoted products were to increase by 50% and those of all limited goods were to decrease by 50%, then we observe increases of all environmental impacts (Figure 7). In particular, forestry products usage (7.9%), nonferrous metal ores usage (7.3%), terrestrial acidification (7.8%), photochemical oxidant formation (8.2%), human toxicity (8.7%), and terrestrial ecotoxicity (8.1%) will be greatly increased, while freshwater usage, agricultural products usage, ferrous metal ores usage, nonmetallic ores usage, solid wastes emissions, and freshwater eutrophication will be slightly increased (Figure 7).

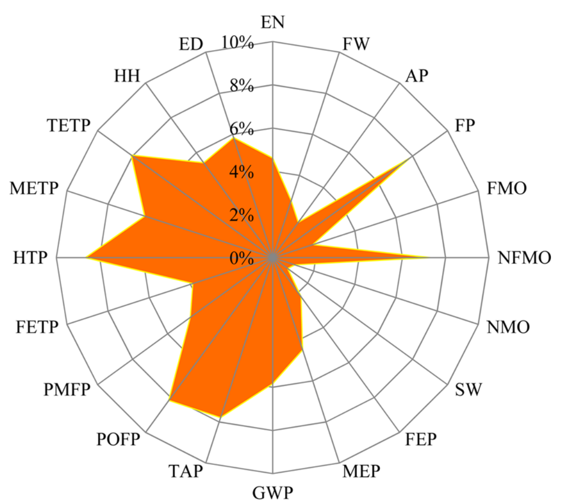

Figure 7. Changes of environmental impacts given an increase in the final demands of promoted industries and a decrease in the final demands of limited industries, both by 50%. Abbreviations in the radar chart represent environmental impacts listed in Figure 6.

In general, China's economic restructuring will cause both environmentally unintended consequences and cobenefits. Comprehensively considering a wider range of environmental impacts from various perspectives is crucially important for effective policy-making.

5. DISCUSSION

5.1. Policy Implications. In order to continue economic growth while ensuring environmental protection, China has been focusing on restructuring its economy. Our results indicate that China's policies on economic restructuring should comprehensively consider a wider range of environmental impacts to avoid unintended environmental consequences and identify cobenefits. Current Chinese five-year plans only focus on selected environmental flows including energy usage, freshwater usage, and emissions of carbon dioxide, sulfur dioxide, nitrogen oxides, chemical oxygen demand, and ammonia nitrogen. Our results show that this will cause environmental problem-shifting and will miss cobenefit opportunities. Two approaches can potentially be useful for China's policy-making to avoid such problems: sustainable materials management (SMM) and integrated policy modeling.

SMM evaluates various types of products on a life cycle basis.[8−10,49,50] By considering a wide range of environmental impacts, China can use the SMM to comprehensively evaluate the environmental performance of industries and set priorities to restructure the economy. SMM also implies that China's environmental policies, including the five-year plans, should cover more resources and pollutants. Fortunately, China has begun to pay attention to heavy metal emissions and resource productivity in recent years. It is expected that additional resources and pollutants will be mandated in China's future five-year plans. Many policy instruments exist for particular SMM targets. Particular policy instruments (e.g., waste recycling policy, energy-saving policy, biofuels policy) usually focus on certain industries or products. The implementation of those policies affects the economy at the same time in different ways. Furthermore, unless such policies are scrutinized from the standpoint of the entire economy, complex interactions across sectors may lead to undesired and unexpected effects, which may offset any benefits gained from their implementation. Understanding the effects of these policies on environmental impacts hence requires integrated policy modeling.

Integrated policy modeling means that policy analysis should focus on the comprehensive effect of all relevant policies instead of particular individual policies. Given that different policies may be interdependent,[21,51] the overall effect of many interrelated policies is not simply equal to the sum of the effects of each individual policy.[52] Integrated policy modeling can account for such complex interactions, and thus can find the best set of policies to maximize the overall effect and minimize the cost of policy implementation. The implementation of many interrelated policies in an integrated manner needs an appropriate institutional structure to coordinate. Such institutional structure does exist in China, in the form of various "leading groups". A leading group is an ad hoc supra-ministerial body formed to coordinate efforts on particular issues across the government, party, and even military systems. China has established such leading groups on a variety of issues, such as financial and economic affairs, foreign affairs, and energy, which have shown feasibility and efficiency of addressing complex policy issues at the national scale. A "leading group" on environmental sustainability formed at the uppermost level could potentially address the difficulty of integrated policy-making for China's increasing environmental impacts.

What general lessons can be drawn from this analysis for the Chinese economy? In many ways, China can be regarded as a representation of many developing countries in its pursuit of rapid and sustainable economic growth. The concepts of unintended environmental consequences and cobenefits in our study can provide insights for sustainable development in other countries. For example, many countries are restructuring their economic structures for a "green economy". Unintended environmental consequences and cobenefit opportunities will largely exist during this process. Comprehensive evaluation of environmental impacts can reveal potentially unintended consequences and identify cobenefit opportunities, providing valuable insights for decision-makers. As we have illustrated in the case of China, an integrated approach is essential to ensure that any policy measures implemented are coordinated by an appropriate government authority in a manner that accounts for their interactions.

5.2. Uncertainties and Recommendations. Uncertainties of results in this study mainly come from two sources: the material flows data and the sector aggregation of China's MIOT. This study covers 49 types of material flows, some of which are estimated under certain assumptions. Factors used for the estimation are usually dated for the current economy. Such uncertainty, however, can be reduced by additional field monitoring in future work.[31] Statistical characterization of such data, such as Monte Carlo simulation, can also be useful in estimating margins of uncertainty of estimated environmental impacts. In addition, there are thousands of products and services within the economy, but the highest resolution of China's MIOTs is in a 135-sector format. Higher sectoral resolution can provide more accurate information.[53] Continuous improvements of China's economic statistics on MIOTs will gradually reduce the uncertainty caused by sector aggregation.

By treating various environmental impacts equally, this study demonstrates the existence of unintended environmental consequences and cobenefit opportunities from policies. For particular economies at certain times, however, there usually are different degrees of concerns among various environmental impacts. Future research will benefit greatly from weighting environmental impacts instead of treating them equally. Many approaches are available to determine subjective weights reflecting value judgments, such as the analytic hierarchy process (AHP)[54−57] based on inputs from all stakeholders. In addition, this study mainly focuses on the environmental aspect of sustainability. Including the social and economic aspects, such as employment and value creation, in this study represents an interesting research avenue for future work.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

(1) The classification of economic sectors in Chinese monetary input-output table; (2) the corresponding relationships between environmental impacts and material flows inventories; (3) detailed data sources for China's material flows inventories; (4) the corresponding relationships between China's adjusted industries and traditional products; and (5) results supporting heat maps in the main text. This material is available free of charge via the Internet at http://pubs.acs.org. Data on China's sectoral material flows and environmental impacts in the spreadsheet format can be found at http://ComplexSustainability.snre.umich.edu/publications/china2007/.

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Notes

The authors declare no competing financial interest.

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