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Decoupling Analysis and Socioeconomic Drivers of Environmental Pressure in China

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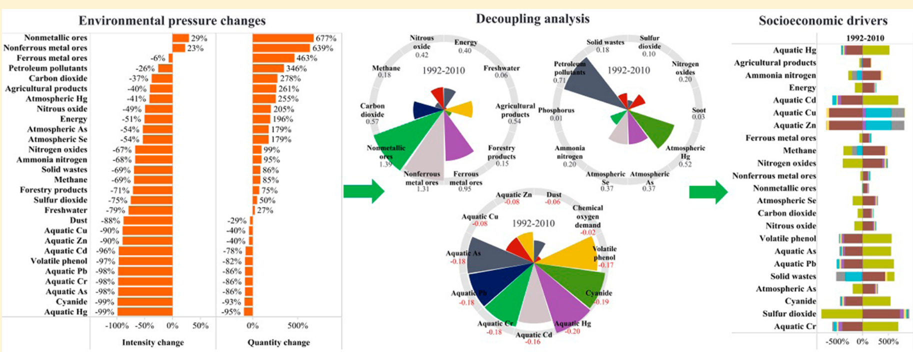
Supporting Information



ABSTRACT: China's unprecedented change offers a unique opportunity for uncovering relationships between economic growth and environmental pressure. Here we show the trajectories of China's environmental pressure and reveal underlying socioeconomic drivers during 1992−2010. Mining and manufacturing industries are the main contributors to increasing environmental pressure from the producer perspective. Changes in urban household consumption, fixed capital formation, and exports are the main drivers from the consumer perspective. While absolute decoupling is not realized, China has in general achieved relative decoupling between economic growth and environmental pressure. China's decoupling performance has four distinguishable periods, closely aligning with nation-wide major policy adjustments, which indicates significant impact of China's national socioeconomic policies on its environmental pressure. Material intensity change is the main contributor to the mitigation of environmental pressure, except for ammonia nitrogen, solid wastes, aquatic Cu, and aquatic Zn. Production structure change is the largest contributor to mitigate ammonia nitrogen emissions, and final demand structure change is the largest contributor to mitigate emissions of solid wastes, aquatic Cu, and aquatic Zn. We observe materialization trends for China's production structure and final demand structure during 2002−2007. Environmental sustainability can only be achieved by timely technology innovation and changes of production structure and consumption pattern.

■ INTRODUCTION

The question of whether environmental pressure can be reduced simultaneously along with economic growth has been intensively discussed.[1,2] As the largest emerging economy, China has achieved spectacular economic growth but also experienced serious environmental degradation in the last 20 years.[3] Currently the second largest economy in the world,[4] China also leads the world in resource consumption and waste emissions.[5,6] For example, China is the world's top consumer of primary energy[7] and minerals,[8] top producer of greenhouse gases (GHGs)[9] and atmospheric mercury,[10] and major

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producer of carbonaceous aerosols.[11] The unprecedented change in China offers a unique opportunity to uncover the relationship between economic growth and environmental pressure,[3,12] which is important for achieving environmental sustainability in both China and the world. This effort in the literature has been limited mainly to energy usage,[13−15] aggregated resource productivity,[16] CO_2 emissions,[17−25] and atmospheric pollutant emissions.[26−28] There still remains a great need and major challenge in comprehensively understanding the relationship between China's economic growth and environmental pressure from multiple aspects.

In this study we explore the environmental pressure of China's economic growth through (1) compiling inventories for 31 types of resources and emissions in China during 1992−2010; (2) examining the relationship between economic growth and environmental pressure during this period using a *decoupling index*; and (3) analyzing relative contributions of six socioeconomic drivers—material intensity, production structure, final demand structure, final demand composition, per capita final demand, and population—to China's environmental pressure.

■ MATERIALS AND METHODS

Environmental Pressure Inventories. We use the amount of material flows to represent environmental pressure.[29,30] Considering 31 categories of material flows including 7 types of resources and 24 types of emissions, we analyze China's environmental pressure inventories from both the producer and consumer perspectives based on an environmentally extended economic input-output (EE-EIO) model,[31] as described by eqs 1 and 2. The producer perspective ties environmental pressure to resident institutions (sectors) generating goods and services, while the consumer perspective ties environmental pressure to final demand by considering life cycle impacts throughout supply chains.[24,26,32−35]

$$\text{Environmental pressure from the producer perspective} = \mathrm{F}\hat{x} \tag{1}$$

$$\text{Environmental pressure from the consumer perspective} = \mathrm{FL}\hat{f_k} \tag{2}$$

Assume that the economy has n sectors and k types of final demands, and interact with the environment through the flows of m categories of materials. The $m \times n$ matrix F indicates the intensity of environmental pressure per unit of each sector's total output. The $n \times n$ matrix $\mathrm{L} = (I - A)^{-1}$ is the *Leontief inverse matrix*,[36] in which I is the $n \times n$ identity matrix and A is the $n \times n$ direct requirement coefficient matrix. The $n \times 1$ vector x stands for each sector's total output, whereas the $n \times 1$ vector f_k represents the k^{th} category of final demand. The notation "$\hat{}$" diagonalizes the column vectors.

Decoupling Index (DI). The DI is used to illustrate environmental pressure of economic growth. It reflects the responsiveness of environmental pressure to unitary gross domestic product (GDP) change during a certain period of time. It is calculated by dividing the relative percentage change of environmental pressure (Δm_i) with the relative percentage change of GDP (ΔGDP) measured in constant price, as eq 3:

$$\mathrm{DI} = \Delta m_i / \Delta \mathrm{GDP} \tag{3}$$

Low values of the DI indicate that an economy is producing lower marginal environmental pressure per unit GDP growth, and hence is relatively decoupling economic growth from environmental pressure.

Structural Decomposition Analysis. We conduct structural decomposition analysis (SDA)[37] for the quantity (v) of environmental pressure, expressing these variables as the product of several independent variables representing factors to be decomposed, as shown in eq 4.

$$v = \mathrm{FLY}_s y_g gp \tag{4}$$

The $m \times 1$ vector v indicates the amount of material flows to represent environmental pressure. The $n \times k$ matrix Y_s represents the share of each of the n sectors in each of the k categories of final demands. The $k \times 1$ vector y_g shows the allocation of total final demand among the k categories of final demands. The scalars g and p in eq 4 are per capita final demand volume and population, respectively.

The decomposition form of eq 4 is

$$\Delta v = \Delta\mathrm{FLY}_s y_g gp + \mathrm{F}\Delta\mathrm{LY}_s y_g gp + \mathrm{FL}\Delta\mathrm{Y}_s y_g gp + \mathrm{FLY}_s \Delta y_g gp + \mathrm{FLY}_s y_g \Delta gp + \mathrm{FLY}_s y_g g\Delta p \tag{5}$$

The terms on the right-hand side of eq 5 represent the contribution to the change of environmental pressure Δv during a certain period of time due to, from left to right, material intensity change ΔF, production structure change ΔL, final demand structure change ΔY_s, final demand composition change Δy_g, per capita final demand change Δg, and population change Δp. Many equivalent decomposition forms exist which is the nonuniqueness issue in the SDA. In this study we use the average of all possible decompositions.[38]

■ DATA SOURCES

Monetary Input−Output Tables. China's monetary input-output tables (MIOTs) in 1992, 1997, 2002, 2007, and 2010 are from *National Bureau of Statistics of China*.[39−43] These MIOTs and the Chinese statistics on resources and pollutants are all based on different sectoral classifications. We aggregate these MIOTs except the 2010 one to the same 45-sector format to be consistent with the sectoral classification for the environmental data (Supporting Information (SI) Table S1). The original 2010 MIOT has only 41 sectors. We disaggregate it into 45 sectors by constructing a prorating matrix based on a binary concordance matrix.[44,45] Total outputs of each sector used to construct the binary concordance matrix are from *China Statistical Yearbook 2011*.[46]

Define the $m \times n$ matrix C as the binary concordance matrix representing how the value is split between the two sectoral classifications, that is, from m sectors to n sectors. The normalized map M corresponding to matrix C is then expressed as eq 6.

$$\mathrm{M} = (\widehat{\mathrm{C}x})^{-1}\mathrm{C}\hat{x} \tag{6}$$

Define the $n \times n$ matrix Z as the intermediate delivery matrix of the MIOT, Y as the diagonal final demand matrix, and V as the diagonal primary input matrix. The original MIOT is then transformed into the one as follows:

$$\mathrm{Z}_{\text{new}} = \mathrm{M}'\mathrm{ZM} \tag{7}$$

$$\mathrm{Y}_{\text{new}} = \mathrm{M}'\mathrm{Y} \tag{8}$$

$$\mathrm{V}_{\text{new}} = \mathrm{VM} \tag{9}$$

In addition, the final demand column named "others" in Chinese MIOTs are removed, as it is regarded as errors of

Table 1. Data Sources for Compiling China'S Material Flow Inventories During 1992−2010

	material flow inventories	data sources
resources	energy	*China Energy Statistical Yearbooks*
	freshwater	*China Environment Yearbooks*; *Annual Statistic Reports on Environment in China*; water usage of service sectors is estimated based on some assumptions.
	biomass (including agricultural products and forestry products) and mineral ores (including ferrous metal ores, nonferrous metal ores, and nonmetallic ores)	*China Agriculture Yearbooks*; *China Statistical Yearbooks*; *China Mining Yearbooks*; *China Statistical Yearbooks*; aggregated data are decomposed based on intermediate allocation data in Chinese MIOTs.
pollutants	water pollutants; conventional air pollutants; and conventional solid wastes	*China Environment Yearbooks*; *Annual Statistic Reports on Environment in China*; *Reports on the first nationwide survey of polluters*
	greenhouse gases; atmospheric heavy metals; crop straws; animal manure; and construction wastes	calculation methods from peer-reviewed literature

different data sources.[20,26,47] Focusing on China's domestic supply chains, we remove imports from Chinese MIOTs using existing method.[48] All MIOTs are converted into ones in 2007 constant price using the double deflation method.[19,20,49−52] Each sector's Producer Price Indexes (PPI) are from *China Statistical Yearbooks*.[46] The SDA is based on the MIOTs in 2007 constant price, whereas environmental pressures from the producer and consumer perspectives are based on original MIOTs in current prices. Chinese MIOTs in 2007 constant prices and related PPI are provided in an excel file as a SI.

Material Flow Inventories. This study considers 7 categories of resource flows and 24 type of waste flows (listed in SI Table S2). Data sources are mainly from government statistics and published literature, as listed in Table 1. The SI provides detailed information on data sources and calculation methods. Detailed material flow inventories are also provided in an excel file as a SI.

Energy. Energy usage data are from *China Energy Statistical Yearbooks*.[53] Energy usage by agricultural sectors is aggregated. We disaggregate this data for each agricultural sector using the intermediate allocation data of energy sources in China's MIOTs.[26] In particular, China's coal consumption during 1996−2003 is regarded to be under-reported.[54] We hence adjust China's coal consumption data in 1997 and 2002 using empirical correlation methods during 1953−2010, as shown in our previous study.[26] Related pollutant emissions calculated based on coal consumption data are also adjusted.

Freshwater. Freshwater usage data in 1992 are unavailable from government statistics. We estimate each sector's freshwater usage in 1992 according to the following method: (1) As freshwater usage data during 1992−1996 are all unavailable, we obtain freshwater usage and wastewater emission data for the year of 1997. Each sector's ratio of freshwater to wastewater is calculated in 1997. (2) We obtain each industrial sector's wastewater emission for the year of 1992 from *China Environment Yearbook 1993*.[55] Assuming that each sector's ratio of freshwater to wastewater in 1992 is the same as that in 1997, we calculate each industrial sector's freshwater usage for the year of 1992 by multiplying its wastewater emission in 1992 with corresponding ratio in 1997. (3) For freshwater usage and wastewater emission data of agriculture, construction, services and residents, they are all unavailable for the year of 1992. We first obtain freshwater usage data of agriculture, construction and residents for the year of 1993 from published literature.[56] We then estimate freshwater usage of agriculture and construction in 1992 by multiplying their freshwater usage in 1993 with ratios of their total output in 1992 to that in 1993 (in 1992 constant prices). We also estimate freshwater usage of residents in 1992 by multiplying their freshwater usage in 1993 with the ratio of the population in 1992 to that in 1993. We assume the freshwater intensity of *Transport, storage and postal services* in 1992 to be the same as that in Chinese 2005 physical input-output table (PIOT).[57,58] Subsequently, freshwater usage of *Transport, storage and postal services* in 1992 is calculated by the freshwater intensity in 2005 PIOT multiplied by corresponding monetary total outputs for the year of 1992 in 2005 constant price. Freshwater usage for other services is regarded as the sum of 55% domestic living water[59] and ecological water compensation and then minus freshwater usage of *Transport, storage and postal services*. Ecological water compensation in 1992 is zero according to *China Statistical Yearbooks 2012*.[60]

Freshwater usage of agriculture, industrial sectors and construction in 1997 and 2002 is from *China Environment Yearbooks*,[61,62] while that in 2007 and 2010 is from *Annual Statistic Reports on Environment in China*.[63,64] Freshwater usage for agricultural sectors from 1997 to 2010 and that for industrial sectors in 1992 and 1997 are highly aggregated. We disaggregate these data using the intermediate allocation data of water in the MIOTs, which is similar to the disaggregation of energy usage data. Freshwater usage for services sectors from 1997 to 2010 is unavailable from Chinese statistics. We assume the freshwater intensity of *Transport, storage and postal services* in 1997, 2002, 2007, and 2010 to be the same as that in Chinese 2005 PIOT.[57,58] Subsequently, freshwater usage of *Transport, storage and postal services* in 1997, 2002, 2007, and 2010 is calculated by the freshwater intensity in 2005 PIOT multiplied by corresponding monetary total outputs in 2005 constant prices. Freshwater usage for other services is regarded as the sum of 55% domestic living water[59] and ecological water compensation and then minus freshwater usage of *Transport, storage and postal services*. Data for domestic living water and ecological water compensation are from *China Environment Yearbooks*[61,62] and *Annual Statistic Reports on Environment in China*.[63,64]

Biomass and Mineral ores. Only aggregated data for biomass and mineral ores are available from government statistics and existing literature. Resource usage data reported for aggregated sectors are disaggregated using intermediate allocation data of sectors representing similar resources in existing MIOTs, based on the unique sectoral price assumption.[57,65] Each sector's biomass usage is calculated based on the intermediate allocation data of agricultural products (the *Cultivation* sector) and forestry products (the *Forestry* sector) in the MIOTs. Each sector's usage of mineral ores is calculated based on the intermediate allocation data of ferrous metal ores (the *Mining and processing of ferrous metal ores* sector), nonferrous metal ores (the *Mining and processing of*

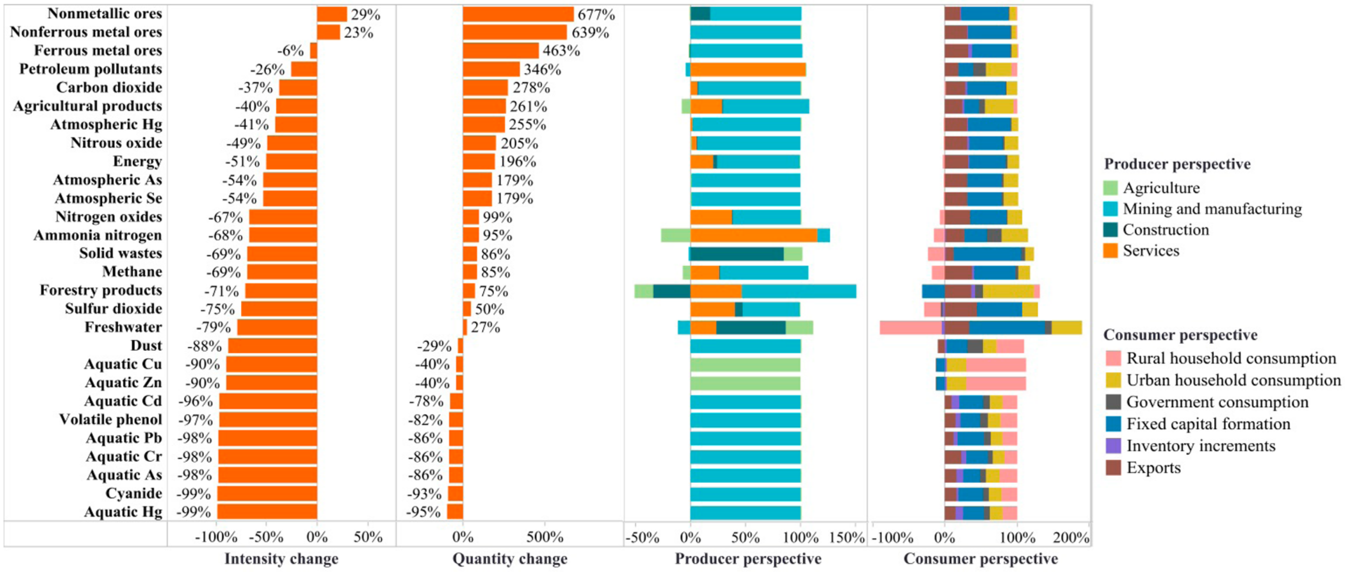

Figure 1. Changes of China's environmental pressure from the producer and consumer perspectives during 1992−2010. Quantity change means the percentage change of environmental pressure measured by the amount of material flows. Intensity change indicates the percentage change of environmental pressure intensity. Intensity is calculated as dividing the quantity by GDP in constant price. GDP in this Figure is equal to the sum of each sector's value added from the Chinese MIOTs in constant prices. The columns for producer and consumer perspectives represent relative contributions of industries and final demand categories to quantity changes of environmental pressure, respectively. For quantity increase/decrease of environmental pressure, positive values from the producer and consumer perspectives indicate that corresponding drivers push the increase/decrease. Detailed data for the producer and consumer perspectives are shown in SI Figures S1 and S2.

nonferrous metal ores sector), and nonmetallic and other ores (the *Mining and processing of nonmetallic and other ores* sector) in the MIOTs.

Taking biomass for example, we first obtain the domestic extraction, imports and exports of biomass from Chinese statistics. For a particular kind of biomass, we calculate its domestic consumption by domestic extraction plus imports and then minus exports.[29,30] For a particular row of monetary input-output tables, domestic consumption also equals to the sum of intermediate allocations, final consumption, and gross capital formation of described materials. We then calculate proportions of the intermediate allocations of each kind of biomass to each sector in domestic consumption of this kind of biomass based on MIOTs. Each sector's biomass usage is finally calculated by its proportion multiplied by domestic consumption of this kind of biomass.

Domestic extraction of agricultural and forestry products in 1992, 1997, 2002, 2007, and 2010 comes from *China Agriculture Yearbooks*.[66−70] Imports and exports of agricultural and forestry products in 2002, 2007, and 2010 are from *China Agriculture Yearbooks*,[68−70] whereas those in 1992 and 1997 are from *China Statistical Yearbooks*.[46] In addition, domestic extraction, imports and exports of mineral ores in 2002, 2007, and 2010 are from *China Mining Yearbooks*.[71−73] Domestic extraction of mineral ores in 1992 and 1997 is obtained from Xu and Zhang's study,[74] while imports and exports of minerals ores in 1992 and 1997 are from *China Statistical Yearbooks*.[46]

Wastes and Emissions. Data for wastes and emissions mainly come from *Annual Statistic Reports on Environment in China*,[63,64] *China Environment Yearbooks*,[55,61,62] and *Reports on the First Nationwide Survey of Polluters*.[75] We use methods proposed by the literature to estimate those data that are not available from government statistics, including GHGs,[76] atmospheric mercury,[26,77−79] nitrogen oxides,[80] crop straws,[81] animal manure,[82] and construction wastes.[82] Aggregated data for emissions are disaggregated according to ratios of total outputs of related sectors. In particular, sludge emission is not included in Chinese environmental statistics on wastewater treatment activities of *Production and distribution of water*. We then extend the scope of solid wastes emissions of *Production and distribution of water* to cover sludge emission. Sludge emission of wastewater treatment activities in 2007 and 2010 are from *Annual Statistic Reports on Environment in China*.[63,64] Detailed methods for obtaining wastes and emissions data are described in the SI.

RESULTS

China's Environmental Pressure during 1992−2010. Our results show that the amount of resources consumed and waste discharged in China during 1992−2010 has sharply increased, except for dust emissions and most water pollutants (Figure 1). During the same period, producing unitary GDP in China requires decreasing amount of resources except for nonmetallic ores and nonferrous metal ores and produces decreasing amount of wastes and emissions (Figure 1).

We attribute China's environmental pressure to different sectors from the producer perspective and to final demands from the consumer perspective. Changes in mining and manufacturing industries are the main direct contributors to the increasing environmental pressure (Figure 1), primarily due to increased production of nonferrous metal ores, chemical products, nonmetallic mineral products, ferrous metals, electric and heat power, and other services (SI Figure S3A). This is also evidenced by the fact that China experienced rapid industrialization and urbanization during 1992−2010, which has driven the increasing demand for raw materials and manufactured products especially for construction materials and fossil fuels. Services dominate emissions of petroleum pollutants and ammonia nitrogen, whose rapid development

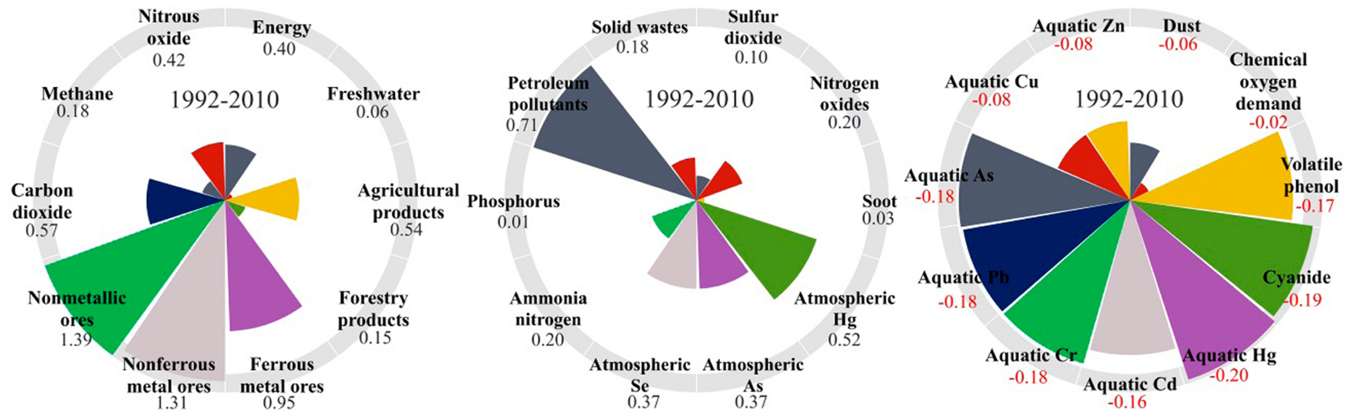

Figure 2. Decoupling indexes indicating environmental pressure of China's economic growth during 1992−2010. The length of each pie indicates the decoupling index value (as labeled) of corresponding environmental pressure. The relationship between economic growth and environmental pressure is *negative decoupling* when the decoupling index is larger than 1 (e.g., nonferrous metal ores and nonmetallic ores in the left subfigure), *relative decoupling* when between 0 and 1, and *absolute decoupling* when smaller than 0 (e.g., the right subfigure).

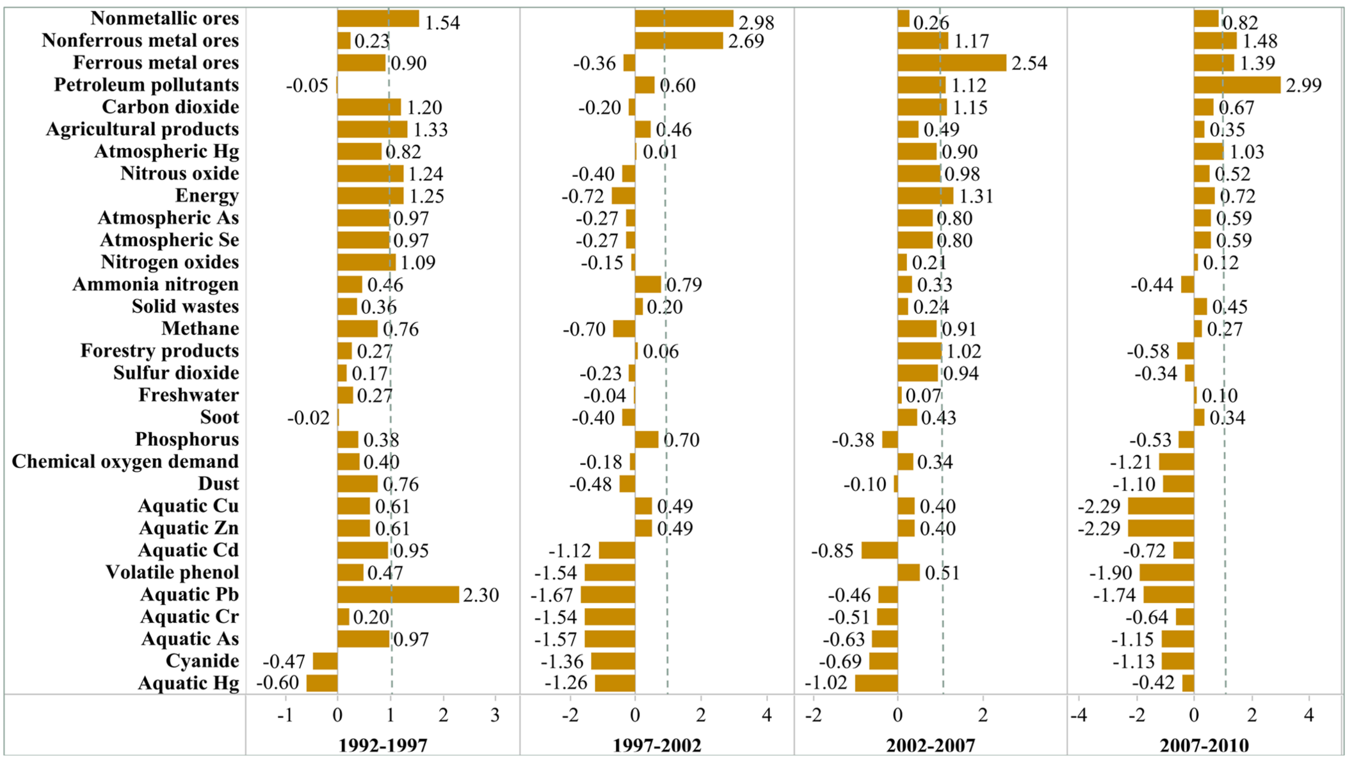

Figure 3. Temporal variation of China's decoupling indexes (horizontal axis) during 1992−2010. The relationship between economic growth and environmental pressure is *negative decoupling* when the decoupling index is larger than 1, *relative decoupling* when between 0 and 1, and *absolute decoupling* when smaller than 0. The dotted lines indicate that the value of decoupling index equals to 1.

mainly induces the increase of petroleum pollutants and ammonia nitrogen emissions (Figure 1). Agriculture dominates emissions of aquatic Cu and aquatic Zn, and its change has the largest contribution to reductions of aquatic Cu and aquatic Zn (Figure 1).

Next we identify underlying drivers for increased environmental pressure throughout supply chains. The increasing final demand for transport equipment, electrical and electronic equipment, construction, and other services is mainly responsible for the increased environmental pressure from the consumer perspective (SI Figure S3A). Changes in urban household consumption, fixed capital formation, and exports are the main drivers for the increased resource usages and waste emissions during 1992−2010 (Figure 1). For the decreased dust emissions and water pollutant discharges, changes in rural household consumption, urban household consumption, and fixed capital formation play an important role (Figure 1). These drivers represent the improved quality of lives in China's households as well as China's large-scale investment in infrastructure development and sharply increased exports in the past two decades. In particular, increased demands for food, transport equipment, construction, and other services dominate the increasing environmental pressure caused by urban household consumption during 1992−2010 (SI Figure S3B). Key drivers in fixed capital formation include the increased demands for general purpose machinery, transport equipment,

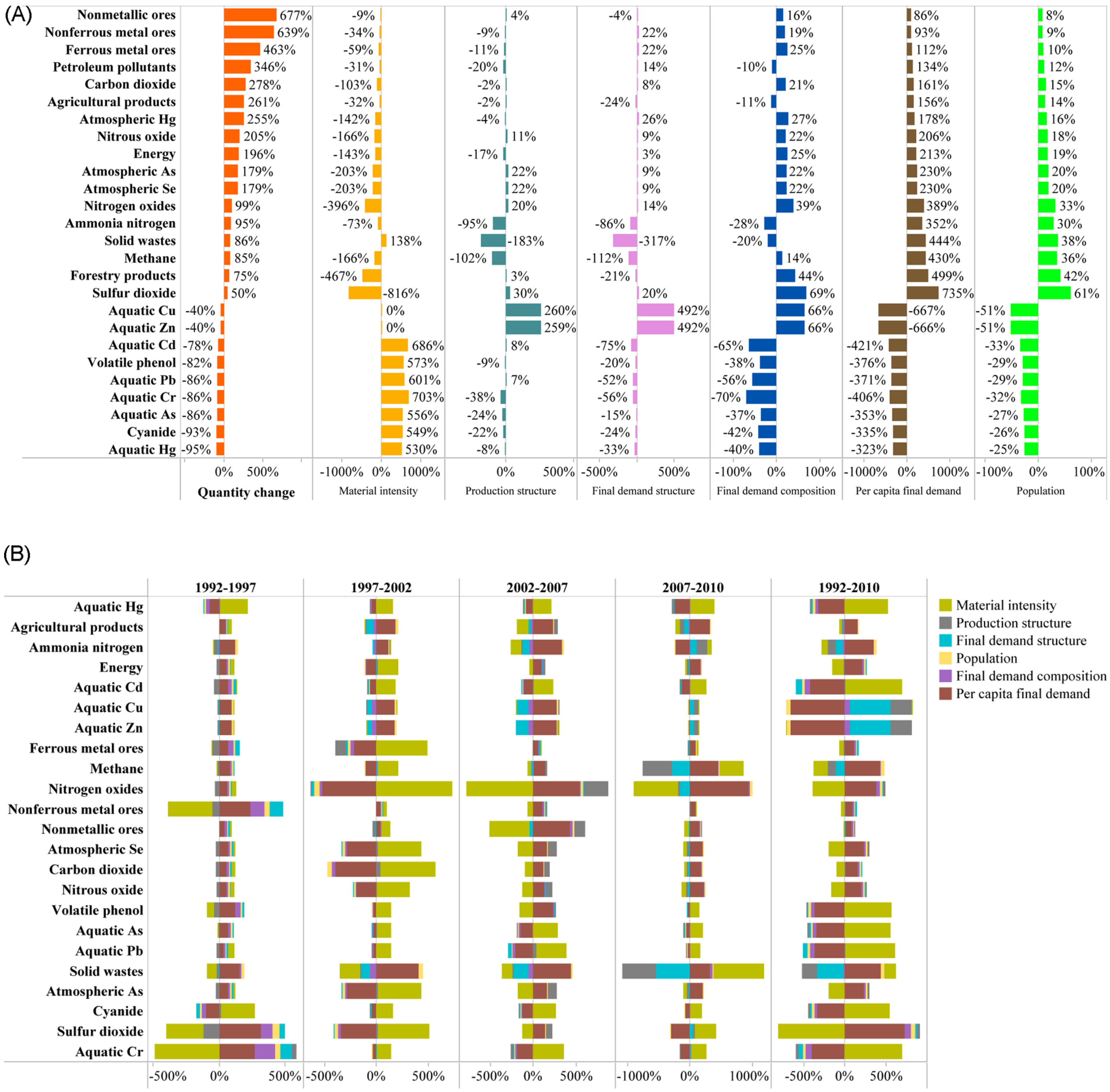

Figure 4. Relative contributions of socioeconomic factors to environmental pressure change during 1992−2010. Taking Figure A for example, the first column named "Quantity change" indicates the percentage change of environmental pressure. The other six columns indicate relative contributions of changes in six socioeconomic drivers. The sum of relative contributions of changes in six socioeconomic drivers for an environmental pressure equals to 100%. For quantity increase/decrease of environmental pressure, positive values indicate that corresponding drivers push the increase/decrease. Detailed quantity results are provided in an excel file as a SI.

electrical equipment, construction, and other services (SI Figure S3B). Increasing exports of textiles, raw chemical materials, equipment and machinery, and other services are also key drivers for increasing environmental pressure (SI Figure S3B).

Decoupling of Economic Growth and Environmental Pressure. *Decoupling* in this study means achieving economic growth with minimum additional environmental pressure. *Negative decoupling*—environmental pressure growing faster than the economy—is observed for the consumption of nonferrous metal ores and nonmetallic ores. China's GDP doubling from 1992 to 2010 is accompanied by the increasing use of nonferrous metal ores and nonmetallic ores by 131% and 139%, respectively (Figure 2). We calculate sectoral decoupling indexes for the usage of nonferrous metal ores and nonmetallic ores based on sectoral added-value in constant prices (SI Figure S8A). *Negative decoupling* in ferrous metals production and other services is the main contributor to the increase of nonferrous metal ores, while *negative decoupling* in metal ores mining and the manufacturing of tobacco, petroleum products and coke, and rubber is the main driver to the increase of nonmetallic ores (SI Figure S8A). For dust emissions and most

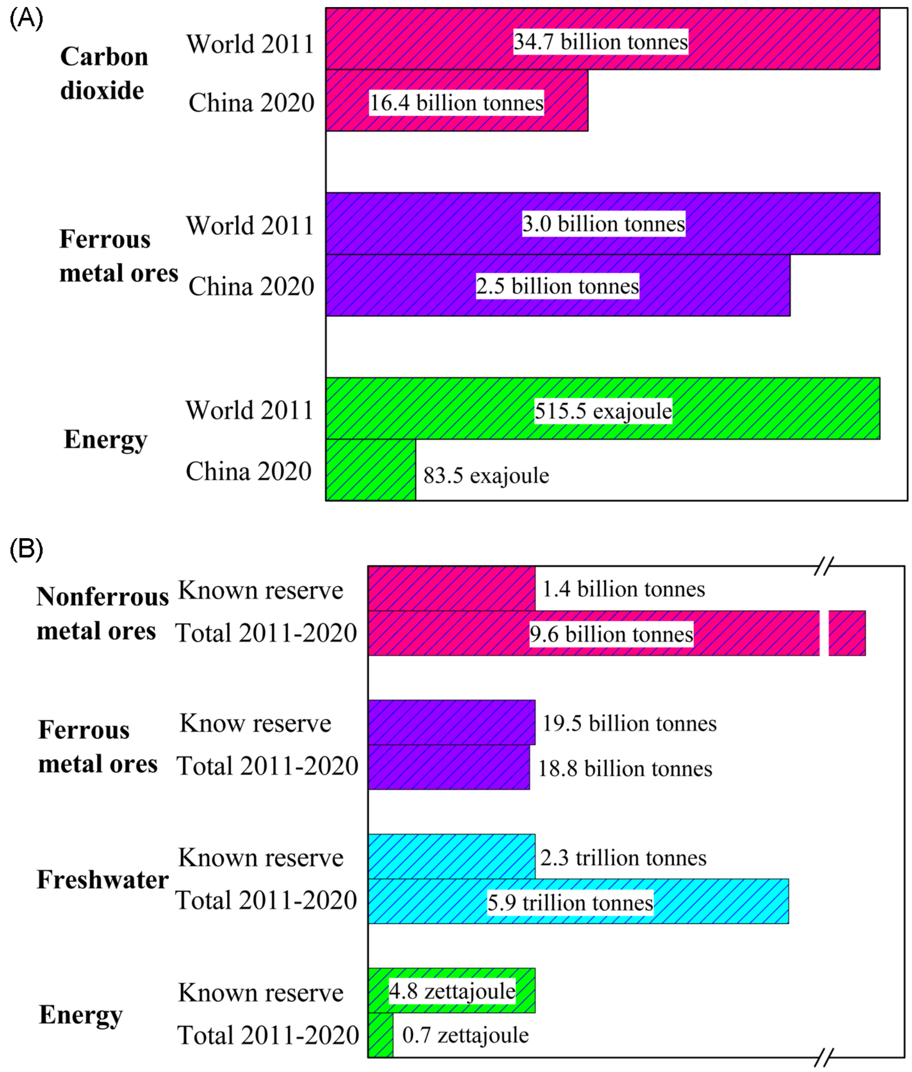

Figure 5. China's possible environmental pressure in 2020 if following development pattern in the past 20 years. Detailed data supporting this Figure are listed in SI Table S4.

water pollutants, there is *absolute decoupling*, meaning that environmental pressure decreases along with economic growth. In particular, dust emissions and the discharge of most water pollutants are reduced by 6% and 2%-20%, respectively, during 1992–2010 when China's GDP is doubled (Figure 2), mainly driven by the *absolute decoupling* in the production of petroleum and natural gas, petroleum products and coke, and fuel gas (SI Figure S8). Economic growth is in *relative decoupling* with the other environmental pressures during 1992–2010, implying that environmental pressure grows slower than the economy (Figure 2). Overall, China's economic growth shows *relative decoupling* from the environmental pressure in general, still far away from *absolute decoupling*.

China's decoupling performance during 1992–2010 can be seen as four distinguishable periods (Figure 3). The economy first shows negative and relative decoupling for the majority of environmental pressures in 1992–1997, followed by absolute decoupling from most environmental pressures in 1997–2002. During 2002–2007, the economy shows negative and relative decoupling again for most environmental pressures, followed by absolute decoupling from water pollutant discharges and relative decoupling from most other environmental pressures in 2007–2010. This notable variation of China's decoupling performance closely aligns with the nation-wide major policy adjustments in China every five years formally known as the Five-Year-Plan (FYP), indicating significant impact of China's national social and economic policies on its environmental pressure. Chinese Central Government began to pay special attention to environmental issues in the ninth FYP (1996–2000), making the decoupling trends better during 1997–2002 than that during 1992–1997. China began the rapid heavy industrialization process during the 10th FYP (2001–2005). Heavy manufacturing which are material-intensive developed quickly in this period, making the decoupling trends become worse during 2002–2007. China's "Industrial Structure Adjustment" in the 11th FYP (2006–2010) lowered the share of heavy manufactured goods, making the decoupling trends become better again during 2007–2010.

Relative Contributions of Socioeconomic Drivers. We examine six drivers impacting and their contributions to China's environmental pressure in the past two decades, including material intensity, production structure, final demand structure, final demand composition, per capita final demand, and population. The results show that increasing affluence measured by per capita final demand is the largest driver for increasing environmental pressure during 1992–2010, followed by the change of final demand composition by different final demands (Figure 4A). The change of production structure measured by the change of the technical coefficient matrix in the input-output model contributed to the reduction of environmental pressure during 1992−2002 and 2007−2010, but induced the increasing environmental pressure during 2002−2007 (Figure 4B). Thus, there is a materialization trend in China's production structure during 2002−2007.

Material intensity reflects the efficiency of utilizing resources and reducing emissions in the economy. Material intensity change is the largest contributor to mitigate environmental pressure, except for ammonia nitrogen, solid wastes, aquatic Cu, and aquatic Zn, during 1992−2010 (Figure 4A). Production structure change is the largest contributor to mitigate ammonia nitrogen emissions, and final demand structure change is the largest contributor to mitigate emissions of solid wastes, aquatic Cu, and aquatic Zn (Figure 4A). The change of final demand structure, sectoral shares in each category of final demand, helped mitigate the environmental pressure during 1997−2002 and 2007−2010, but contributed to the increasing environmental pressure during 1992−1997 and 2002−2007 (Figure 4B). Thus, there is a materialization trend in China's final demand structure during 1992−1997 and 2002−2007.

The absolute decoupling observed for most water pollutants during 1992−2010 is mainly due to the changes of material intensity, except for aquatic Cu and aquatic Zn (Figure 4A). For the absolute decoupling of emissions of aquatic Cu and aquatic Zn, changes in production structure and final demand structure are primary contributors (Figure 4A).

DISCUSSION

Policy Implications. In November 2012, the Chinese government proposed a target for doubling its GDP from the 2010 level by 2020. If China follows its development pattern in the past 20 years, doubling GDP will result in large-scale increase of resource demand and waste emissions. For example, China's industrial energy consumption and ferrous metal ore usage by 2020 might be equivalent to 16% of the world's energy consumption and 84% of the world's ferrous metal ore production in 2011, respectively (Figure 5A). CO_2 emissions in China by 2020 might be equivalent to 47% of the world's total CO_2 emissions in 2011 (Figure 5A). China's demand for freshwater and nonferrous metal ores during 2011−2020 might exceed its known resource reserves, equivalent to 252% and 690% of its known reserves in 2011, respectively (Figure 5B). The total consumption of ferrous metal ores during 2011−2020 might also approach China's known reserve in 2011 (Figure 5B). In addition, China's current known fossil fuel reserves might maintain its economic growth for only 66.7 (=1/0.15 × 10) years (Figure 5B). This would imply either a slowdown of China's economy due to resource constraints or transferring resource demand to other parts of the world, such as Africa, and consequentially environmental impacts in those areas.

China will continue to pursue economic growth to improve life quality, but with slower and slower growth speed. China's population is also expected to grow slowly in the near future. The growth of economy and population will still push the increase of environmental pressure. According to Figure 2, to achieve absolute decoupling, the material intensity needs to be reduced by a factor of at least 2.39, 2.31, 1.95, and 1.01−1.71 (values are equal to the decoupling index plus 1.00) for nonmetallic ores, nonferrous metal ores, ferrous metal ores, and other materials, respectively. China still has considerable potential to reduce material intensity, such as developing renewable energy sources and low-emission technologies.[83] Timely technology innovation is hence crucial for reducing environmental pressure, which can also stimulate economic growth.[84] However, only relying on technology innovation may not be enough for stabilizing environmental pressure;[85] special attention should also be paid to change production structure and consumption pattern.

During 1992−2002, China's economic growth was dominated by light manufacturing sectors. However, production structure change induced increasing environmental pressure in 2002−2007 due to the rapid development of heavy manufacturing industries.[46] During 2007−2010, China focused on upgrading traditional manufacturing and eliminating outdated technologies, known as "Industrial Structure Adjustment". These actions greatly changed the production structure and led to the mitigation of environmental pressure during this period.

During 2002−2007, China's final demand significantly shifted from labor-intensive manufactured goods to heavy industrial products[26] with higher material intensity.[86] Thus, final demand structure change contributed to the environmental pressure mitigation during 1997−2002, but to the increase of most environmental pressures during 2002−2007. Since 2007, China's "Industrial Structure Adjustment" has lowered the share of heavy manufactured goods in the final demand, leading to the environmental pressure mitigation during 2007−2010.

Our results also show that a particular driver has different performances for different environmental pressures. For example, changes in rural household consumption have primary contribution to the reductions of aquatic Cu and Zn, but small influence on other environmental pressures (Figure 1). Moreover, production structure change has positive contribution to the reductions of aquatic Cu and Zn, but negative contribution to the mitigation of aquatic Cr and As (Figure 4A). This indicates that adjusting a driver during policy-making can produce unintended environmental consequences and cobenefits. Establishing a "leading group" at institutional level to coordinate related institutions during policy-making is necessary to improve policy efficiency.[47]

In general, China needs timely technology innovation to reduce material intensity and should further optimize its production structure and consumption pattern to decouple its economic growth from increasing environmental pressure. A "leading group" at institutional level will minimize policy cost by avoiding unintended environmental consequences and utilizing cobenefits. These actions are beneficial for the sustainability of both China and the world.

Uncertainties and Recommendations. Uncertainties of results in this study mainly come from data sources. In this study, we have obeyed the following principles to minimize uncertainties of environmental pressure inventories: (1) using China's official national statistical data if available, (2) using empirical regression analysis to adjust the statistics when there are discoveries of data under-reporting or over-reporting, such as the treatment of China's energy statistics during 1996−2003,[26] and (3) using widely accepted estimation methods when official statistics are unavailable, such as the estimation of GHG emissions,[76] atmospheric mercury emissions,[26,77−79] and crop straws emissions.[81] Most of our data for material flow inventory compilation are from China's official statistics, as shown in Table 1, which can be regarded as relatively reliable data sources. Improving China's environmental statistics is beneficial for reducing uncertainties of data sources. China's first polluter census in 2007[75,87] is a good start to improve the environmental statistics. In addition, we only focus on China's domestic supply chains in this study. There are also interconnections between China and other countries, which should be another concern of future studies.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information provides additional contents on data sources and results. This material is available free of charge via the Internet at http://pubs.acs.org.

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