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Article

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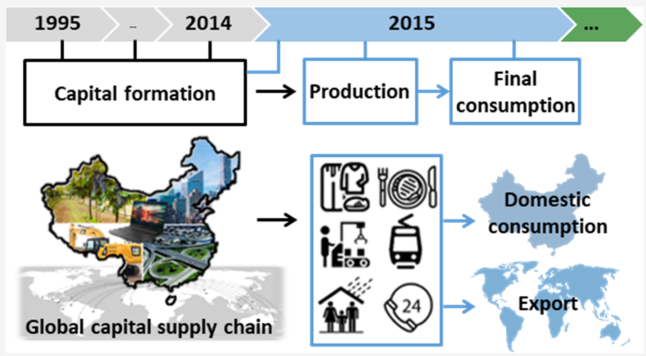
ABSTRACT: China's rapid growth was fueled by investments that grew more than 10-fold since 1995. Little is known about how the capital assets acquired, while being used in productive processes for years or decades, satisfy global final consumption of goods and services, or how the resource use and emissions that occurred during capital formation are attributable to past or future consumption. Here, enabled by a new global model of capital formation and use, we quantify the linkages over the past 2 decades and into the future between six environmental pressures (EPs) associated with China's capital formation and attributable to Chinese as well as non-Chinese consumption. We show that only 35% of the capital assets acquired by China from 1995 to 2015, representing 32−39% of the associated EPs (e.g., water consumption, greenhouse gas (GHG) emissions, and metal ore extractions), have been depreciated, while the majority rest will serve future production and consumption. The outsourcing of capital services and the associated EPs are considerable, ranging from 14 to 25% of depending on the EP indicators. Without accounting for the capital−final consumption linkages across time and space, one would miscalculate China's environmental footprints related to the six EPs by big margins, from −61% to +114%.



1. INTRODUCTION

In a period of unprecedented economic growth, China increased its share of world gross domestic product (GDP) from less than 2% in 1990 to nearly 15% in 2015.[1] With investment accounting for 34−48% of the country's GDP since 1990, China produced or imported capital assets such as livestock for breeding, power plants, communication networks, and computer software. The production of capital assets, however, typically requires more resources and generates more pollution than that of noncapital goods.[2−4] From 1995 to 2015, 22 million km^2 of land use, 630 km^3 of blue water consumption, 759 EJ (exajoules) of primary energy use, and 10 Gt (gigatonnes) of metal ore extractions were appropriated in China for its capital development, accounting for 15, 21, 41, and 39% of the national totals, respectively; outside of China, another 16 million km^2 of land, 135 km^3 of blue water, 130 EJ of energy, and 7 Gt of metal ore extractions were associated with China's capital expansion (Supporting Information Figures S1 and S2).

However, little is known about how significant environmental pressures (EPs) generated in capital assets production link to global final consumption, i.e., the satisfaction of human needs through the goods and services produced with the help of those assets. Conventionally, consumption-based accounting (CBA) is used to investigate the attribution of various EPs to the national final demand of products (i.e., goods and services), yielding the environmental footprints (EFs) of nations.[5−7] The EFs of nations are thus the EPs occurring throughout the supply chain of goods and services allocated to the final consumption of those goods and services.[3,8] Historically, CBA was based on multiregional input−output (MRIO) tables representing the production, trade, and consumption of products in a single year, so it could not represent the use of capital assets stretching over longer time periods. While CBA has become a crucial tool for assessing the sustainability, efficiency, and equity of resource use from the perspective of consumers and government,[3,9,10] current CBA models fail to capture capital's role in production and consumption and hence misallocate the EPs embodied in capital assets (EP^K) in EF assessment. Unlike noncapital goods that are purchased for consumption, capital assets are bought to be used in productive processes. Therefore, intuitively, EP^K shall be

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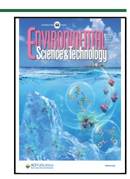

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allocated throughout the lifetime of the assets, i.e., over years or even decades, to those who consume the finished products made using the assets directly and indirectly, regardless of the geographical location of the assets or the final consumption. Neglecting capital's spatiotemporal features, conventional CBA models treat the purchase of capital assets in the same way as the purchase of noncapital goods, assigning EP^K to the purchasing country and the purchasing year.[11]

Acknowledging the economic and environmental significance of capital, there have been a few endeavors to tackle the methodological and data challenges related to modeling capital assets as intermediate inputs used in production, also known as "capital endogenization" in input−output analysis.[12−19] Consistently, they show that the inclusion of capital as intermediate inputs leads to substantial redistribution of carbon and material footprints across industries and countries. The implications are especially significant for countries featuring high capital investments and export, such as China, and the final consumption of services related to real estate, public administration, transport and storage, and education, which usually require a lot of material- and carbon-intensive capital assets, such as buildings and infrastructure.[16,17] However, the intertemporal features of EP^K remain unaddressed since capital assets used for year n's production and final consumption are of different age cohorts produced based on the production recipe, trade networks, and environmental intensities of year n, $n-1$, $n-2$, $n-3$,....[17] Such temporal dynamics are inherent to the retrospective distribution of historically generated resource use and emissions to current final consumption, critical for understanding the temporal trends and thus the future needs of resources and emissions for capital formation.

By developing a new capital endogenization method that addresses the above temporality issue, we present a novel analysis on how China's capital development and the associated resource use and emissions over the past 2 decades (1995−2015) are linked to meeting the final consumption of China and other countries throughout this time period. Our analysis focuses on six indicators of environmental pressures: primary energy use, blue water consumption, land use, metal ore extractions, nonmetallic mineral mining, and greenhouse gas (GHG) emissions, because they represent priority resources and development goals in China and globally. With the linkages quantified, we then reassess China's environmental footprints. Our results indicate an urgent need to quantify and emphasize economic and environmental efficiency for the decision making of capital use and investment.

2. MATERIALS AND METHODS

The new method for endogenizing capital in input−output analysis is achieved through three main steps:

(1) trace and allocate the contribution of year t's capital investments to year n's interindustry production networks depicted by year n's MRIO tables, obtaining $D^K_{t,n}$ ($t \le n$);

(2) quantify the supply chain-wide EPs that were generated during the production of the capital inputs $D^K_{t,n}$ based on year t's production structures and environmental intensities of production activities depicted by year t's MRIO tables, obtaining ($F^K_{t,n}$);

(3) attribute $\sum_t^n F^K_{t,n}$ to year n's final consumption based on year n's production−consumption systems depicted by year n's MRIO tables, obtaining $\sum_t^n EF^K_{t,n}$.

We describe the three steps in detail in the following sections. The MRIO tables are obtained from EXIOBASE 3,[20] which offers a time series of MRIO tables and environmental intensity estimates ranging from 1995 to 2015 for 44 countries (28 EU member plus 16 major economies) and 5 rest-of-the-world regions. EXIOBASE 3 offers MRIO tables with a high level of consistent sectoral (200 products) and environmental (417 emission categories and 662 material and resources categories) details.

2.1. Constructing the Global Capital Consumption Matrix $D^K_{t,n}$.

The process to construct $D^K_{t,n}$ is composed of five segments. First, annual capital consumption from the capital investment times series is calculated. We model year n's consumption of asset a, which was invested in year t by sector s in country i, as capital depreciation ($D^K_{i,a,s,t,n}$) using the geometric method (eq 1). The geometric method is a standard practice adopted by national and international statistical agencies and researchers for constructing capital consumption time series.[21] Geometric depreciation depicts each year the asset is depreciated by a constant percentage of the previous periods value. The capital consumption (depreciation) represents the gradual depreciation of assets via output generation, i.e., wearing out, getting lost or breaking down, or becoming obsolete through advances in technology or shifts in consumer demand.

$$D^K_{i,a,s,t,n} = \delta^K_{i,a,s}(1 - \delta^K_{i,a,s})^{n-t} I^K_{i,a,s,t} \quad (1)$$

Capital investment values ($I^K_{i,a,s,t}$) and the corresponding depreciation rates ($\delta^K_{i,a,s}$) are obtained from three macroeconomic datasets: EU KLEMS (2009 release and 2017 release),[22] WORLDKLEMS,[23] and the Penn World Table (PWT) 9.1.[24] Details of the investment data and depreciation rates obtained from the three data sources, such as the classifications of the investing sectors and assets, are presented in Supporting Information A. For instance, Austria's annual capital investment data ($I^K_{\text{Austria},t}$) are specified by 34 investing sectors and 10 assets, obtained from EU KLEMS (2017 release); the 34 sectors and 8 assets are further detailed in Table S3. The δ values are constant throughout the years of our simulation (1995−2015) but vary by asset a, the capital investing sector s, and the capital investing country i. Note, we assume that the capital investing sectors are also the capital consuming sectors. Mathematically, $D^K_{i,t,n}$ is a two-dimensional matrix variable with the same shape as $I^K_{i,t}$: sectors that invested and consumed assets are aligned by columns, assets are aligned by rows, while each element in $D^K_{i,t,n}$ is calculated through eq 1. All elements in $I^K_{i,t}$ and $D^K_{i,t,n}$ are measured in million euros (€) of year t.

The second step is to link capital consuming sector s to capital producing sector $s*$ through capital asset a. Each element in the transformed $D^K_{i,t,n}$ matrix is $D^K_{i,s*,s,t,n}$. Such a transformation is achieved through "asset-capital producing sector" concordance tables created in a prior study.[17] The capital producing sectors follow the 200-product sectoral classification adopted by EXIOBASE 3.

We then further distinguish the capital producing sectors to those located in country i and those outside of country i, i.e., capital assets that were imported. Such allocation is based on year t's fixed capital formation matrix $Y^K_{i,t}$ available in EXIOBASE 3. $Y^K_{i,t}$ presents country i's investment records in year t, specifying the expenditures across 200 sectors and 49 countries/regions. This step transforms the $D^K_{i,t,n}$ matrix again, expanding the number of rows (producing sectors) from 200 to 9800 (49 × 200). Throughout the second and third steps, the sum of all

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elements $D^{K}_{i,t,n}$ remains the same and the unit of each element is still million euros (€) of year t.

Next, we map the capital consuming sectors s that are defined in the macroeconomic datasets (e.g., 34 sectors in EU KLEMS 2017 release) to EXIOBASE 3's 200-product sectoral classification. Such transformation is based on the sector concordance tables created in a prior study.[17] This step transforms $D^{K}_{i,t,n}$ to a matrix with 9800 rows specifying capital production across the world and 200 columns specifying capital consuming sectors in country i. The transformation does not change the sum of all elements in $D^{K}_{i,t,n}$, and the unit of each element is still million euros (€) of year t.

The final step in creating the global capital consumption matrix $D^{K}_{t,n}$ is to horizontally concatenate $D^{K}_{1,t,n}$, $D^{K}_{2,t,n}$, ..., $D^{K}_{49,t,n}$ for each of the 49 countries/regions specified in EXIOBASE 3. $D^{K}_{t,n}$ is thus a 9800 × 9800 matrix with capital producing and capital consuming sectors along rows and columns, respectively; each element records the quantity of assets that were invested in year t and consumed (i.e., depreciated) in year n, measured in million euros (€) of year t.

2.2. Quantifying the Supply Chain-Wide EPs Attributable to the Consumed Capital Assets. Equation 2 calculates the supply chain-wide EPs that occurred in year t and are attributable to $D^{K}_{t,n}$:

$$F^{K}_{t,n} = \widehat{S}_t L_t D^{K}_{t,n} = \widehat{S}_t (I - A_t)^{-1} D^{K}_{t,n} \quad (2)$$

For any EP indicator (e.g., GHG emissions), S_t is a row vector of direct resource use or emissions intensities of economic activities (e.g., kg/million € of year t), specified by 200 sectors and 49 countries/regions (1 × 9800) and obtained from EXIOBASE 3. L_t is the Leontief inverse matrix,[25] describing the supply chain-wide economic outputs associated with per unit finished goods and services in year t (9800 × 9800). L_t is calculated from A_t (9800 × 9800 in EXIOBASE 3), with each element $a_{i,j}$ representing the amount of intermediate input i directly required per unit of output j, and a 9800 × 9800 identity matrix I.

$F^{K}_{t,n}$ is a 9800 × 9800 matrix. Aligned along the rows are the 9800 country−sector pairs that directly extracted resources or released emissions in year t while partaking in the supply chains of the capital assets produced in year t—the supply chain-wide connections are made through L_t. The 9800 columns specify the country−sector pairs that consumed the corresponding capital assets in year n, i.e., following the columns of $D^{K}_{t,n}$. Intuitively, $F^{K}_{n} = \sum_t^n \hat{S}_t L_t D^{K}_{t,n}$ captures the supply chain-wide EPs that were generated from year t to year n when the capital inputs allocated to year n's production activities (i.e., $\sum_t^n D^{K}_{t,n}$) were produced. The unit of each element in $F^{K}_{t,n}$ and F^{K}_{n}, e.g., if the EP indicator is GHG emissions, is kg/year.

2.3. Re-assessing the Environmental Footprints (EFs). From the consumption perspective, which is the key concept taken by environmental footprint accounting, F^{K}_{n} is ultimately attributable to final consumption in year n (Y^{C}_{n}). That is, the consumed capital ($\sum_t^n D^{K}_{t,n}$) and the associated EPs (F^{K}_{n}) are attributable to production activities in year n (x_n), and those production activities ultimately serve for final consumption in year n. Thus, we calculate the environmental intensities of year n's production activities owing to capital consumption as S^{K}_{n} (eq 3).

$$S^{K}_{n} = \varphi F^{K}_{n} \widehat{x_n}^{-1} \quad (3)$$

where x_n is a 1 × 9800 column vector that records economic outputs of the 9800 country−sector pairs in year n, obtained from EXIOBASE 3 and measured in million euros (€) of year n. φ is a 1 × 9800 summation vector of ones. S^{K}_{n} is a row vector describing the resource use or emission intensities for the 9800 country−sector pairs that consumed $\sum_t^n D^{K}_{t,n}$ in year n. The unit of each element in S^{K}_{n}, e.g., if the EP indicator is GHG emissions, is kg/million € of year n.

We can then reassess the environmental footprints of countries (eqs 4 and 5)

$$\mathrm{EF}^{K}_{n} = S^{K}_{n} L_n Y^{C}_{n} \quad (4)$$

$$\mathrm{EF}_{n} = \mathrm{EF}^{C}_{n} + \mathrm{EF}^{K}_{n} + \mathrm{EF}^{HH}_{n} = S_n L_n Y^{C}_{n} + \mathrm{EF}^{K}_{n} + \mathrm{EF}^{HH}_{n} \quad (5)$$

The final consumption matrix Y^{C}_{n} (9800 × 49) is obtained from EXIOBASE 3 and describes the finished goods and services, specified by the 9800 country−sector pairs, that are consumed by 49 countries/regions in year n. EF^{K}_{n}, a 1 × 49 vector, captures the historical EPs that are attributable to Y^{C}_{n} owing to the capital consumption attributable to year n's production activities ($\sum_t^n D^{K}_{t,n}$). EF^{C}_{n} (1 × 49) captures the EPs that occurred in year n and are attributable to Y^{C}_{n} owing to the noncapital inputs used in year n's production activities, which can be calculated by the conventional CBA approach. EF^{HH}_{n} captures the EPs directly released by households in year n and is available in EXIOBASE 3.

3. RESULTS

3.1. Annual Profiles of China's Capital Consumption. Approximately one-third of the $36.7 trillion (2015 US dollars) capital assets invested by China during 1995−2015 were consumed by 2015, while two-thirds remain effective for future productive purposes. In most years, the assets acquired by nonindustrial enterprises (i.e., agriculture, construction, and services), such as livestock for breeding, orchards, residential and office buildings, and intellectual property, dominated the capital consumption. In 2015, they accounted for 55% of the nation's total capital consumption, while the consumption of industrial equipment accounted for about another 40% (Figure 1A).

When examining annual profiles and trends, it is important to note that the consumption of capital goods invested before 1995 was not accounted for in our analysis because data for earlier capital investments and production practices are sparse or not readily available for many countries. As a result, our estimates of capital consumption are conservative, especially for the early years in our modeling period (e.g., year 1995). For the later years, the impacts of neglecting pre-1995 capital investments become much smaller (see additional analysis in Supporting Information G and Figure S3). Starting with 2011, less than 1% of the capital consumption came from capital goods invested in 1995. Such a low presence of early investments is likely unique to China, owing to the rapid growth of capital investments and stocks in recent years (Figure S1) as well as the relatively short life span of capital assets in China compared to other countries (Table S9). Based on the temporal results of 2011−2015, when the implications of neglecting pre-1995 investments are deemed low, our results show that the capital assets consumed in China averaged 4−4.6 years old (Figure 1B).

Our results also reveal that only 8% of the capital consumption originated from capital assets imported from outside of China, and this fraction decreased from 14% in 1995

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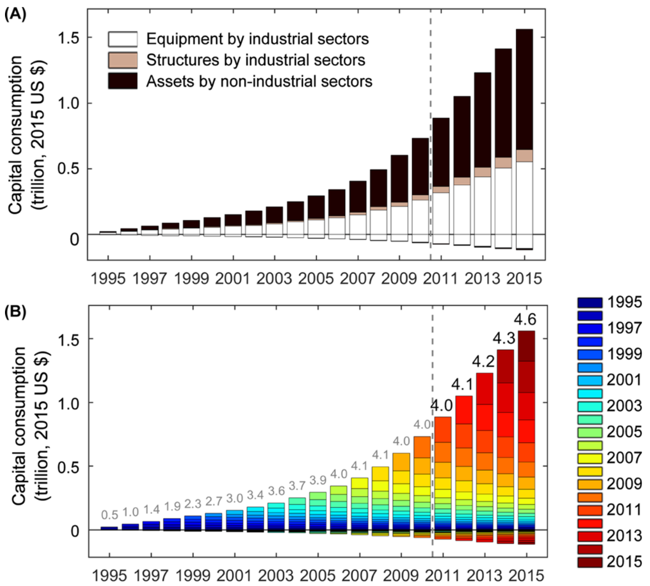

Figure 1. China's annual capital consumption (D^{K}_{China}) profile by type of capital asset (A) and by year of investment (B). In both (A) and (B), capital assets purchased from China are plotted above the abscissa and those imported from other countries are plotted below the abscissa; all assets were invested during 1995−2015. The vertical dashed line illustrates that capital invested in 1995 accounted for less than 1% of annual capital consumption since 2011; further analysis indicates that pre-1995 investment likely accounts for a small fraction of the capital consumption profile since 2011 (Supporting Information G and Figure S3). In (A), "Equipment by industrial sectors" covers computing, communication, and transport equipment,other machinery and equipment, and computer software and databases; "Structures by industrial sectors" includes nondwelling buildings and structures; "Assets by nonindustrial sectors" are invested by nonindustrial enterprises (agriculture, construction, and service sectors) and include residential structures, cultivated assets, research and development, and other intellectual property products assets. In (B), numbers on top of the bars show the weighted average age of capital assets consumed.

to 7% in 2015 (Figure 1B). However, for industrial equipment and machinery, imported capital goods consistently accounted for a much larger share (16−21%) of the capital consumption throughout the 20 years (Table S10). Japan, Germany, and the United States have been the most important producers of capital assets consumed, accounting for half of the imported assets consumed in China's economic development. South Korea is playing an increasingly important role in China's capital investment and economic production. During 1995−2015, the industrial equipment and machinery imported from South Korea to China tripled; by 2015, capital assets imported from South Korea accounted for nearly 13% of China's consumption of imported capital goods, increased from 5% in 1995.

3.2. Attributing the EPs Embodied in China's Capital Consumption to Global Final Consumption. Significant resource use and emissions occurred during the production of the capital assets consumed in China between 1995 and 2015. This sums to 311 EJ primary energy used, 300 km^3 blue water consumed, 14.4 million km^2 land used, 5.4 Gt metal ore extracted, 42.7 Gt nonmetallic mineral mined, and 23.8 Gt GHG emitted (Figure 2). They account for 32% (metal ore extractions) to 39% (blue water consumption) of the six EPs embodied in the assets China acquired between 1995 and 2015, and 1% (land use) to 8% (nonmetallic mineral extractions) of the global resource use and emissions in the same period. The EPs are ultimately attributable to final consumption of goods and services, primarily in China. Across all six indicators, the final consumption of services in China dominates the EPs embodied in the capital consumption. Depending on the pressure indicators, 40% (metal) to 53% (mineral) of the EPs are attributable to real estate, public administration, education, and health services consumed in China (Table 1). This is not surprising given the real estate booms in China.[26] The country's fast expansions of public services and medical services[27] also led to large purchases of capital goods, such as nonresidential structures, machinery, and equipment.

Of all six indicators, more than half of the foreign-driven resource use and emissions are owing to the consumption in 22 OECD countries (country names are detailed in Table S1) and nearly a quarter are attributed to the United States alone. The strong linkages between capital consumption in China and overseas final consumption are consistent with the crucial role that export activities have played in China's (accounting for 20% of China's GDP over 1995−2015) and the global economy. Different from China's domestic consumption, the foreign consumption of manufactured products dominates the capital-related EPs. Quite surprisingly, for the product category of "Radio, TV, communication equipment, and apparatuses," foreign consumption even exceeded the domestic consumption in its attribution to all six environmental pressures (Table 1). China is known as the world's "manufacturing powerhouse." In 2016, two-fifths of the world's semiconductors were produced in China. Similarly, China was involved in the production of more than half of the world's mobile phones and produced almost all of the printed circuit boards.[28] A varying fraction of the EPs embodied in the consumed assets occurred outside of China, as the supply chains of the capital assets are distributed around the globe (B in Figure 2). The foreign implications are especially significant regarding metal and land, accounting for 43% of the metal ore extractions and 33% of the land use embodied in the consumed capital assets. Latin America is the most important region for the metal ore extractions underlying China's capital development, contributing 16% (38%) in the total (foreign) metal ore extraction embodied in the consumed assets. As for the foreign land use embodied in China's capital consumption, it is mainly distributed in economies in transition, other Asian countries, and OECD countries, accounting for 28, 25, and 22%, respectively. In contrast, only 3% of the nonmetallic mineral extractions and 8% GHG emissions embodied in the China's capital consumption occurred outside of the country. Moreover, EPs associated with China's capital investment and depreciation as well as the domestic and foreign implications are contrasted and further discussed in Supporting Information E and Figure S2.

3.3. EFs of China over 1995−2015 Distinguishing between Capital and Noncapital Goods. By linking the resource use and emissions associated with both capital and noncapital goods produced and consumed worldwide in 1995−2015 to China's final consumption in the same time period, we reassessed China's footprints in the six indicators (**b1** in Figure 3). We find that, depending on the pressure indicators, 8% (land)——46% (metal) of China's footprints are owing to capital consumption (gap between **b1** and **a2** in Figure 3). More than 40% of the metal ore extractions and land use and as little as 4% of the mineral mining and GHG emissions related to capital consumption occurred outside of China (gap between **b1** and **b2** in Figure 3). Note that the capital consumption attributable to China's final consumption include capital assets located in

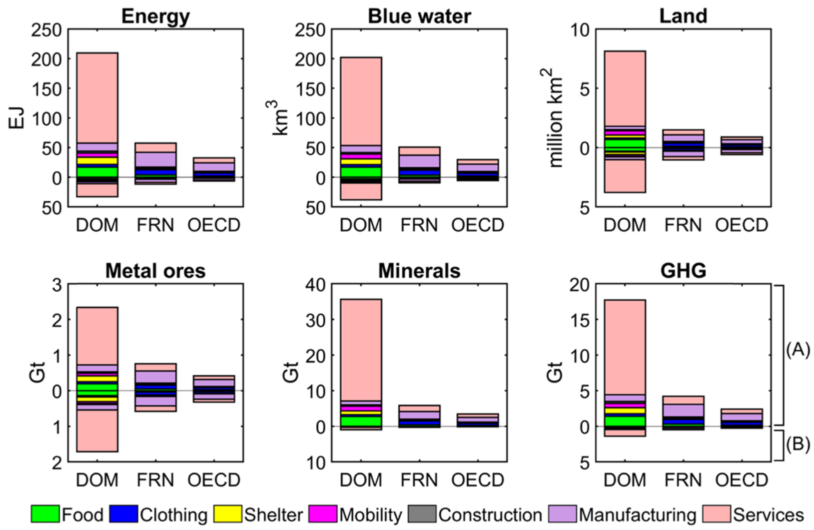

Figure 2. Attributing the resource use and emissions of China's capital consumption over 1995−2015 to the satisfaction of global consumption in the same period. Each subplot illustrates cumulative EP from 1995 to 2015, i.e., $\sum_{n=1995}^{2015}\sum_{t=1995}^{n} F_{\mathrm{China}}^{\mathrm{K}}$. Monetary values of the capital consumption are presented in Figure 1 on an annual basis, considering asset investment from 1995 to 2015. In each subplot, the three bars correspond to the final consumption of Chinese domestic (DOM), foreign countries (FRN), and the Organization for Economic Co-operation and Development-1990 countries (OECD), respectively; the resource use or emissions that occurred in China and in other countries are plotted above and below the abscissa, respectively. To highlight the linkages between capital consumption and human needs satisfaction, here, we categorized the finished goods and services defined by the 200-product categories in EXIOBASE 3 into seven main categories of human needs (see Table S8).

Table 1. Product Categories of Domestic (D) and Foreign (F) Final Consumption that Account for the Highest EPs Related to China's Capital Consumption from 1995 to 2015[a]

	energy		blue water		land		metal		minerals		GHG	
footprint type	D	F	D	F	D	F	D	F	D	F	D	F
product category												
radio, TV, communication equipment, and apparatus		3		2		2		3		1		2
motor vehicles, trailers, and semitrailers	2	1	1	1	1		2	2			1	1
supporting transport and travel agency services	2		2		3		2		3		2	
real estate services	17		18		20		15		24		19	
computer and related services	2		2		2		2		2		2	
public administration, defense, social security	14	2	14	2	16	2	13	2	17	1	15	2
education services	6		7		7		6		7		7	
health and social work services	6	1	5	1	5	1	6	2	5		5	1
sum of the rest product categories	29	14	29	13	28	11	29	15	27	10	28	13
total	78	22	80	20	83	17	75	25	86	14	80	20

[a]Product categories shown made at least a 2% contribution to the cumulative EPs related to China's capital consumption over 1995−2015 (i.e., $\sum_{n=1995}^{2015}\sum_{t=1995}^{n} F_{\mathrm{China},t,n}^{\mathrm{K}}$). All values are shown in percentages (%); blank indicates a value of less than <1%. Product categories are based on EXIOBASE 3's 200-product classification without further aggregation.

China as well as in other countries, as long as they were used to meet the final consumption of goods and services in China.

Our results demonstrate that, by treating capital investment the same as final consumption of noncapital goods or neglecting capital investment in footprint accounting, existing CBA methods grossly misrepresent China's EFs. For instance, in 2015, the energy, GHG, mineral, and metal footprints accounted by conventional CBA and considering a country's capital invesments as a part of its final demand (**a1** in Figure 3) are 41−114% higher than the reassessed values that result from allocating the EPs of historical investments to current and future, domestic and foreign, consumption (**b1** in Figure 3). Most of the overestimates come from failing to assign historical EPs to future consumption. Those assets will serve final consumption both in China and abroad; hence, the embodied EPs need to be assigned accordingly. On the other hand, if the EPs associated with the production of capital assets are omitted from footprint accounting (**a2** in Figure 3), China's footprints in 2015 would be underestimated by 12−61% depending on the pressure indicators.

The EFs attributable to capital consumption (EF^K) can be effectively reduced by increasing the effective life spans of the capital assets (Table 2). When all capital assets are used for a longer time in China, with a −10% change of the depreciation rates, China's EF^K in 2015 would be reduced by 4.2−6.3% across the six indicators. In the case of buildings, due to different internal (e.g., inadequate architectural design, poor construction quality, and noneffective operation and maintenance plans) and external (e.g., demolishing buildings to pursue commercial profits, poor planning) factors, the actual life span of buildings in China is about 30 years, much shorter than their designed life spans and the actual life spans of buildings in developed countries, which range from 44 to 132 years.[29,30] For the purpose of using capital assets more efficiently and reducing the

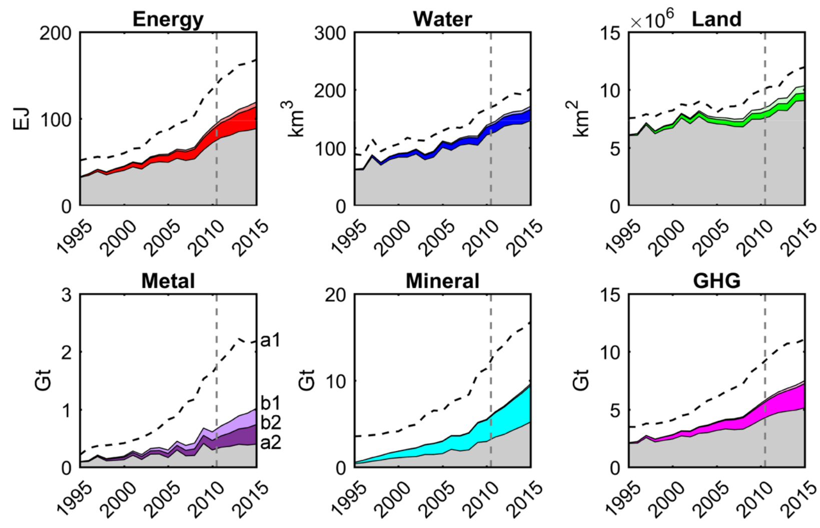

Figure 3. Environmental footprints of China's final consumption during 1995−2015 assessed by different footprint accounting methods and scopes. Lines **a1**, **a2**: The area between **a1** and **a2** represents EPs associated with China's capital investments since **a1** shows China's capital investments in year *n* and the related EPs included as part of China's EFs in year *n* using the conventional CBA approach, while **a2** shows the conventional EF accounting with capital investments and related EPs omitted. Line **b1** shows the reassessed EFs of China using our capital endogenization method. The colored area between **b1** and **a2** indicates China's EFs related to capital consumption in year *n* (the consumed assets were produced in year 1995, ..., *n*, within China and abroad); the area between **a2** and **b2** indicates the resource use and emissions that occurred within China, while the area between **b1** and **b2** indicates the resource use and emissions that occurred outside of China. For the EFs related to capital consumption, we further specified the years when EPs were generated in Figure S5. Gray dashed line: additional analysis indicates that pre-1995 investments, which were neglected here due to data limitation, will likely have small impacts on the values of the reassessed EFs in recent years (e.g., 2011−2015 on the right side of the gray dashed line; see Supporting Information G and Figure S3).

Table 2. Changes of China's EF^K in 2015 as a Function of Depreciate Rates (i.e., Effective Life Spans) of Capital Assets Located in China[a]

changes in depreciation rate (%)	footprint type					
	energy	water	land	metal	mineral	GHG
−10[b]	−2.2%	−1.9%	−1.5%	−2.8%	−0.8%	−1.7%
−10[c]	−0.1%—0	−0.1%—0	−0.1%—0	−0.1%—0	−0.1%—0	−0.1%—0
−10[d]	−4.5%	−4.2%	−4.6%	−4.2%	−6.3%	−5.1%
−10[b,c,d]	−6.7%	−6.1%	−6.1%	−7.0%	−7.0%	−6.8%
+10[b]	2.0%	1.8%	1.4%	2.6%	0.7%	1.6%
+10[c]	0—0.1%	0—0.1%	0—0.1%	0—0.1%	0—0.1%	0—0.1%
+10[d]	4.2%	3.8%	4.2%	4.0%	5.9%	4.8%
+10[b,c,d]	6.2%	5.6%	5.6%	6.6%	6.6%	6.3%

[a]A smaller (larger) depreciation rate indicates a longer (shorter) life span; type of capital assets. [b]Equipment by industrial sectors. [c]Structures by industrial sectors. [d]Assets by nonindustrial sectors.

related EPs, several strategies could be considered in China, such as implementing more stringent quality standards for new capital projects, enhancing the maintenance of existing capital goods, as well as promoting circular economy strategies. Moreover, the EF^K values appear to be the least sensitive to life span changes of industrial structures in China (e.g., warehouses, thermo-electricity plants) mainly due to these structures' already long life spans.

4. DISCUSSION

Capital development influences the attainment of all 17 of the sustainable development goals (SDGs).[31] Our research, for the first time, reveals how China's vast capital development from 1995 to 2015, and the associated emissions and resource use are linked to the satisfaction of various human needs, both inside and outside of China. It also reveals that, from the consumption perspective, foreign countries, especially the rich ones, out-sourced capital services to China, enabled by the China's capital development and export-oriented economy, and displaced the associated EPs to China and other places in the world. The capital-embodied EPs are mainly attributable to meeting final consumption of services; principally real estate, public administration, education, and medical services in China; and the final consumption of manufactured products in other countries. The capital−final consumption linkages and the temporal cross-country interdependencies of the capital development are crucial yet neglected by the existing literature that use conventional CBA methods.

Our results also shed light on future capital development. We show that 65% of the capital assets acquired by China from 1995 to 2015 remain effective for productive purposes after 2015, and 61% or more of the six EPs embodied in the acquired assets are attributable to final consumption beyond 2015. Based on the trend of 2011−2015, China's overall capital stock is still growing, measured in monetary values as well as by the amount of embodied resource use and emissions (Figure S6). The

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compositions of the investing sectors has been relatively stable, with the real estate, transportation and storage, public administration, and utility sectors dominating the capital stock and the embodied EPs. A recent study highlights that the level of residential floor area in China has surpassed that of the United Kingdom on a per capita basis and there is huge overcapacity of steel mills and power plants.[30] Together the findings indicate an urgent need to emphasize economic and environmental efficiency in the decision making of capital investment.

More broadly, our results demonstrate the importance of establishing long-term visions in assessing the resource and emission implications of achieving the SDGs through capital development. For instance, accounting for the temporal dynamics of GHGs emitted during current capital development and their attributions to future capital use can help make equitable carbon budgets at the national and global scales. On the other hand, due to the long life spans of capital assets, future generations are locked into operating and maintaining historically developed capital stocks and the specific use patterns of assets, which may no longer meet future needs of resource efficiency and climate change mitigation.[30,32] This line of research is beyond the scope of this analysis but worth future explorations.

Capital endogenization and its conceptual values are still quite new for both researchers and policy makers. Understanding and accounting for the temporal dynamics of capital goods in economic production and in allocating the associated EPs accordingly will benefit sustainability science and policy making, where intergenerational implications are considered to be important. In the dynamic framework, we further highlight the effects of asset life span and the roles of a global capital market for mitigating the considerable EPs associated with capital development and use. A few measures, such as implementing more stringent quality standards for new capital projects, enhancing the maintenance of existing capital goods, as well as promoting circular economy strategies, can effectively decrease the associated resource usage and emissions. Prior studies show that short-lived buildings in China have contributed to considerable environmental pressures that could have been avoided,[33,34] consistent with what we found in the sensitivity analysis (Table 2). More specifically, prior studies indicate that if average building life span in China can be extended from 30 years to around 50 years, 5.8 km^3 water and 426 Mt CO_2 emissions would be avoided in 1 year.[34] Future capital development in China needs to specify both "quantity" (more than \$94 trillion US dollars predicted by 2040)[31] and "quality" (resource-efficient, low-impact). Technology advancements, a major driver that historically reduced the consumption of key resources (e.g., water, or energy) and the emissions,[35,36] will also be a promising means for future sustainable capital development.

It is crucial to note that the magnitude of EPs we quantify here (e.g., 300 km^3 blue water consumption and 14.4 million km^2 land use) do not directly indicate the magnitude of environmental impacts (e.g., water stress and biodiversity loss).[37] The latter are more complex to infer and depend upon many characteristics of the pressures, such as timing and location. For example, the environmental impacts of metal ore extraction, mineral mining, and GHG emissions importantly depend on temporal accumulations of the pressures. GHGs emitted in 1 year have limited implications on global climate change; resource depletion of metal and minerals are often a result of years' or decades' unsustainable extraction activities. For water use, the environmental impact in the form of water stress typically depends on temporary appropriations, unless the water is appropriated from nonrenewable groundwater bodies. The impacts of land use are more complex, depending on temporal characteristics (i.e., short-term, permanent, or irreversible), the types of land-using capital (e.g., orchards and other plantations of trees, residential dwellings, or industrial buildings), and land use change (e.g., from natural to human-dominated habitats). Moreover, some limitations of the method we use remain, primarily due to the limited availability of capital data in earlier years and developing countries. Future efforts are still needed, however, to develop a consistent dataset of capital investment and consumption, with a higher resolution of capital goods and economic sectors and longer time series and involving more countries. Note that although this study focused on China, capital development accounts for a considerable fraction of resource use and emissions in many other countries and globally. The methodological improvement will become increasingly important as the global production networks linked by international trade continue to grow.

We also note that the new capital model we used in this analysis relies on various types of data—the MRIO data, capital time series, and resource use and emissions accounts, all of which come with uncertainty, as documented in refs 20, 22, 24. Therefore, the estimates we present here are calculated results and need to be interpreted with caution. Crucially, our new model addressed the temporality issue left unresolved by prior capital endogenization efforts (e.g., refs 12, 13, 15−17), which assume that capital consumed today was produced using today's technology. As illustrated by Figure S7, the EF estimates appear sensitive to this methodological improvement. However, such improvement comes with a trade-off. For each year from 1995 to 2015, the two key technology-related variables regarding production configuration and environmental intensity of production are described by matrix A and matrix S in EXIOBASE 3, respectively. As such, the temporal scope of our analysis is constrained to 1995−2015, the temporal coverage of EXIOBASE 3, although capital statistics in earlier years are available and earlier capital investments can have non-negligible implications to the EF estimates of 1995−2015. To the best of our knowledge, EXIOBASE 3 offers one of the longest time series of MRIO data and the corresponding environmental accounts among all global MRIO databases. Moreover, our model and the EP estimates are constrained by the aggregated capital asset classifications. In comparison to earlier capital endogenization studies, our work already benefited from the refined capital classifications enabled by recent capital data development efforts. Capital goods are classified into 8−10 asset categories in recent releases of KLEMS,[22] which cover most European Union countries, the United States, Japan, and Australia; 3−7 asset categories in WORLDKLEMS[23] for China, South Korea, and Canada; and 4 asset categories in PWT 9.1 for the rest of countries/regions (see Tables S2−S7). Although such asset resolution suffices many economic studies, it remains rough for capturing the varying production inputs and environmental intensities associated with the production of different assets. Finally, the temporal dynamics of the capital goods owned and used by final consumers (i.e., households, governments, and nongovernmental organizations) are yet to be modeled and captured by future works. The consumption of those capital goods may follow different depreciation patterns than those used for economic production. Unlike the capital used in economic production, the beneficiaries of the capital

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goods owned by final consumers are more straightforward and will not change with time unless the capital goods enter the second-hand markets and get a new owner. However, all capital goods, whether owned by producers or final consumers, will eventually enter waste streams, either though disposal or through recycling and integration into further production. To the best of our knowledge, those flows are yet to be modeled and accounted for in future research.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.0c07263.

Methods and extended results that supplement the main results and discussion points (PDF)

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Notes

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■ REFERENCES

(1) The World Bank. *World Development Indicators*, 2019.

(2) Jiang, M.; Behrens, P.; Wang, T.; Tang, Z. P.; Yu, Y. D.; Chen, D. J.; Liu, L.; Ren, Z. J.; Zhou, W. J.; Zhu, S. J.; He, C. F.; Tukker, A.; Zhu, B. Provincial and sector-level material footprints in China. *Proc. Natl. Acad. Sci. U.S.A.* **2019**, *116*, 26484−26490.

(3) Tukker, A.; Bulavskaya, T.; Giljum, S.; de Koning, A.; Lutter, S.; Simas, M.; Stadler, K.; Wood, R. Environmental and resource footprints in a global context: Europe's structural deficit in resource endowments. *Global Environ. Change* **2016**, *40*, 171−181.

(4) Zheng, X. Z.; Wang, R.; Wood, R.; Wang, C.; Hertwich, E. G. High sensitivity of metal footprint to national GDP in part explained by capital formation. *Nat. Geosci.* **2018**, *11*, 269−273.

(5) Hertwich, E. G.; Peters, G. P. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. *Environ. Sci. Technol.* **2009**, *43*, 6414−6420.

(6) Wang, R.; Zimmerman, J. Hybrid Analysis of Blue Water Consumption and Water Scarcity Implications at the Global, National, and Basin Levels in an Increasingly Globalized World. *Environ. Sci. Technol.* **2016**, *50*, 5143−5153.

(7) Wiedmann, T. O.; Schandl, H.; Lenzen, M.; Moran, D.; Suh, S.; West, J.; Kanemoto, K. The material footprint of nations. *Proc. Natl. Acad. Sci. U.S.A.* **2015**, *112*, 6271−6276.

(8) Wiedmann, T.; Lenzen, M. Environmental and social footprints of international trade. *Nat. Geosci.* **2018**, *11*, 314−321.

(9) Hoekstra, A. Y.; Wiedmann, T. O. Humanity's unsustainable environmental footprint. *Science* **2014**, *344*, 1114−1117.

(10) Weinzettel, J.; Hertwich, E. G.; Peters, G. P.; Steen-Olsen, K.; Galli, A. Affluence drives the global displacement of land use. *Global Environ. Change* **2013**, *23*, 433−438.

(11) Gao, Z.; Geng, Y.; Wu, R.; Zhang, X.; Pan, H.; Jiang, H. China's CO2 emissions embodied in fixed capital formation and its spatial distribution. *Environ. Sci. Pollut. Res.* **2020**, *27*, 19970−19990.

(12) Lenzen, M. Primary energy and greenhouse gases embodied in Australian final consumption: an input−output analysis. *Energy Policy* **1998**, *26*, 495−506.

(13) Chen, Z.-M.; Ohshita, S.; Lenzen, M.; Wiedmann, T.; Jiborn, M.; Chen, B.; Lester, L.; Guan, D.; Meng, J.; Xu, S.; et al. Consumption-based greenhouse gas emissions accounting with capital stock change highlights dynamics of fast-developing countries. *Nat. Commun.* **2018**, *9*, No. 3581.

(14) Berrill, P.; Miller, T. R.; Kondo, Y.; Hertwich, E. G. Capital in the American carbon, energy, and material footprint. *J. Ind. Ecol.* **2020**, *24*, 589−600.

(15) Miller, T. R.; Berrill, P.; Wolfram, P.; Wang, R.; Kim, Y.; Zheng, X.; Hertwich, E. G. Method for endogenizing capital in the United States Environmentally-Extended Input-Output model. *J. Ind. Ecol.* **2019**, *23*, 1410−1424.

(16) Södersten, C.-J.; Wood, R.; Wiedmann, T. The capital load of global material footprints. *Resour., Conserv. Recycl.* **2020**, *158*, No. 104811.

(17) Södersten, C.-J. H.; Wood, R.; Hertwich, E. G. Endogenizing capital in MRIO models: the implications for consumption-based accounting. *Environ. Sci. Technol.* **2018**, *52*, 13250−13259.

(18) Södersten, C.-J.; Wood, R.; Hertwich, E. G. Environmental Impacts of Capital Formation. *J. Ind. Ecol.* **2018**, *22*, 55−67.

(19) Södersten, C.-J. H.; Lenzen, M. A supply-use approach to capital endogenization in input−output analysis. *Econ. Syst. Res.* **2020**, *32*, 451−475.

(20) Stadler, K.; Wood, R.; Bulavskaya, T.; Södersten, C. J.; Simas, M.; Schmidt, S.; Usubiaga, A.; Acosta-Fernández, J.; Kuenen, J.; Bruckner, M.; et al. EXIOBASE 3: Developing a time series of detailed environmentally extended multi-regional input-output tables. *J. Ind. Ecol.* **2018**, *22*, 502−515.

(21) O'Mahony, M.; Timmer, M. P. Output, input and productivity measures at the industry level: the EU KLEMS database. *Econ. J.* **2009**, *119*, F374−F403.

(22) EUKLEMS EU KLEMS Growth and Productivity Accounts. http://www.euklems.net/.

(23) WORLDKLEMS WORLD KLEMS Initiative. http://www.worldklems.net/index.htm.
(24) Feenstra, R. C.; Inklaar, R.; Timmer, M. P. The Next Generation of the Penn World Table. *Am. Econ. Rev.* **2015**, *105*, 3150−3182.
(25) Leontief, W. Environmental Repercussions and the Economic Structure: An Input-Output Approach. *Rev. Econ. Stat.* **1970**, *52*, 262−271.
(26) Glaeser, E.; Huang, W.; Ma, Y.; Shleifer, A. A real estate boom with Chinese characteristics. *J. Econ. Perspect.* **2017**, *31*, 93−116.
(27) Meng, X.; Gregory, R.; Wang, Y. Poverty, inequality, and growth in urban China, 1986−2000. *J. Comp. Econ.* **2005**, *33*, 710−729.
(28) Allen, G. C. *The Economist*; China's Grip on Electronics Manufacturing Will be Hard to Break, 2018.
(29) Wang, J. J.; Zhang, Y. R.; Wang, Y. F. Environmental impacts of short building lifespans in China considering time value. *J. Cleaner Prod.* **2018**, *203*, 696−707.
(30) Hertwich, E. G.; Ali, S.; Ciacci, L.; Fishman, T.; Heeren, N.; Masanet, E.; Asghari, F. N.; Olivetti, E.; Pauliuk, S.; Tu, Q.; et al. Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review. *Environ. Res. Lett.* **2019**, *14*, No. 043004.
(31) Thacker, S.; Adshead, D.; Fay, M.; Hallegatte, S.; Harvey, M.; Meller, H.; O'Regan, N.; Rozenberg, J.; Watkins, G.; Hall, J. W. Infrastructure for sustainable development. *Nat. Sustain.* **2019**, *2*, 324−331.
(32) Davis, S. J.; Caldeira, K.; Matthews, H. D. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. *Science* **2010**, *329*, 1330−1333.
(33) Andrews, C. J. Regional differences in emissions reduction opportunities. *Energy Policy* **1993**, *21*, 1011−1024.
(34) Cai, W.; Wan, L.; Jiang, Y.; Wang, C.; Lin, L. Short-Lived Buildings in China: Impacts on Water, Energy, and Carbon Emissions. *Environ. Sci. Technol.* **2015**, *49*, 13921−13928.
(35) Guan, D.; Hubacek, K.; Weber, C. L.; Peters, G. P.; Reiner, D. M. The drivers of Chinese CO2 emissions from 1980 to 2030. *Global Environ. Change* **2008**, *18*, 626−634.
(36) Zhou, F.; Bo, Y.; Ciais, P.; Dumas, P.; Tang, Q.; Wang, X.; Liu, J.; Zheng, C.; Polcher, J.; Yin, Z.; Guimberteau, M.; Peng, S.; Ottle, C.; Zhao, X.; Zhao, J.; Tan, Q.; Chen, L.; Shen, H.; Yang, H.; Piao, S.; Wang, H.; Wada, Y. Deceleration of China's human water use and its key drivers. *Proc. Natl. Acad. Sci. U.S.A.* **2020**, *117*, 7702−7711.
(37) Steffen, W.; Richardson, K.; Rockstrom, J.; Cornell, S. E.; Fetzer, I.; Bennett, E. M.; Biggs, R.; Carpenter, S. R.; de Vries, W.; de Wit, C. A.; Folke, C.; Gerten, D.; Heinke, J.; Mace, G. M.; Persson, L. M.; Ramanathan, V.; Reyers, B.; Sorlin, S. Sustainability. Planetary boundaries: guiding human development on a changing planet. *Science* **2015**, *347*, No. 1259855.

https://doi.org/10.1021/acs.est.0c07263
Environ. Sci. Technol. 2021, 55, 6421−6429