ENVIRONMENTAL STUDIES

Forty years of reform and opening up: China's progress toward a sustainable path

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After 40 years of reform and "opening up," China has made remarkable economic progress. Such economic prosperity, however, has been coupled with environmental degradation. We analyze diverse long-term data to determine whether China is experiencing a decoupling of economic growth and environmental impacts, and where China stands with respect to the Sustainable Development Goals (SDGs) in terms of reducing regional division, urban-rural gap, social inequality, and land-based impacts on oceans. The results highlight that China's desire to achieve "ecological civilization" has resulted in a decoupling trend for major pollutants since 2015, while strong coupling remains with CO_2 emissions. Progress has been made in health care provision, poverty reduction, and gender equity in education, while income disparity continues between regions and with rural-urban populations. There is a considerable way to go toward achieving delivery of the SDGs; however, China's progress toward economic prosperity and concomitant sustainability provides important insights for other countries.

INTRODUCTION

The year 2018 marks the 40th anniversary of China's reform and opening up. Decades of rapid economic growth have put undeniable pressure on the environment and exacerbated several societal issues, but China now stands at the crossroad of a future development alternative. Decoupling economic growth from ecological impact has been central to the ambition of realizing national and United Nations' Sustainable Development Goals (SDGs) (*1*, *2*). The optimistic view suggests that improvement in science and technology, transformations in policy, and a shift in societal values will alleviate environmental impacts (*3*, *4*). Relative decoupling has been achieved at both national and global levels (*5*). From 1900 to 2009, per capita use of resources increased by 119.5% globally, whereas the resources consumed in producing one unit of gross domestic product (GDP) declined by 62.7% (*6*). However, this relative decoupling is still insufficient to realize comprehensive global sustainability. Apart from challenges for environmental decoupling, the concept of sustainable development has also focused on poverty reduction, health care improvement, the provision of high-quality education, social inequality mitigation, and ocean sustainability (*7*–*9*). For example, globally, 783 million people live below the international poverty line and 57 million primary age children are out of school. Approximately 20% of large marine ecosystems are expected to suffer from eutrophication. Faced with these challenges, the UN SDGs set a systematic framework with 17 goals considering three dimensions of performance on sustainability—economic, social, and environmental (*10*).

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In 1978, facing the disrupted economy following the Cultural Revolution, the Chinese people desired to emancipate their minds and break with the traditional and constraining economic system. The reform was inspired by a group of farmers in Xiaogang village of Anhui province who created the Household Contract Responsibility System that replaced the People's Commune System and stimulated farmers' enthusiasm and innovation, which was gradually endorsed by different levels of the government (*11*). Special economic zones were first established as test beds in four coastal cities (Shenzhen, Zhuhai, and Shantou in Guangdong Province; Xiamen in Fujian Province) to explore the approach to opening up and to provide a platform for reform across the whole of China (*12*). After 40 years of development, China has become the world's second largest economy. The contribution from China to the global GDP has increased from 2.4 to 14.8% (*13*), the per capita GDP from 380 to 54,000 CNY, the per capita disposable income from 170 to 24,000 CNY (*14*), and the outward foreign direct investment from 297 to 1,235,925 million CNY (*15*).

Economic prosperity, however, has resulted in notable environmental challenges. A hypothesis was proposed to present the relationship between environmental pressure and per capita income, which is an inverse U–shaped curve, beginning with a coupling stage where environmental pressure increases with per capita income to a certain level and then moving to a decoupling stage where environmental pressure decreases. In terms of China's ambition to deliver the UN 2030 SDGs, the focus has been toward addressing social progress, especially inter-generation equity and intra-equity, poverty alleviation, health and well-being, equal education, and gender equality (*16*). In addition, both the SDGs and Future Earth have drawn increasing attention to the ocean, specifically conservation and sustainable utilization of marine resources (*17*).

In this study, a comprehensive analysis was conducted on the economic, social, and environmental performance of China to address the following questions: (i) Is China in the process of transforming from a coupled to a decoupled economy? (ii) What has been China's performance in eliminating regional divisions in economic development, resource availability, and energy consumption? (iii) Is there still a rural-urban gap in income, education, and health care? (iv) What progress has been achieved in alleviating social inequality in education,

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job opportunity, and poverty? and (v) How far is China from achieving integrated land-ocean development in terms of the sufficiency and sustainability of marine resource utilization?

Here, we report spatial and statistical analyses of key performance metrics based on national statistical and survey data available for 31 provinces excluding Hong Kong, Macao, and Taiwan (Supplementary Materials), and present large-scale overviews of China's sustainability performance and an analysis of decoupling trends.

RESULTS

Transformation from coupling to decoupling

Over the past 40 years, China's GDP has expanded by an annual average of 9.6% to 74.35 trillion CNY (*14*), with an overall 30-fold increase (fig. S1A). This growth accelerated from 1978 to 2007 but has decreased in recent years. Such rapid economic growth has been achieved at the expense of natural resources and the environment (*3*), which has led to excessive emissions including wastewater, waste gas, solid waste, and carbon dioxide that extended from the developed east region to the undeveloped west region (figs. S1, B to H, and S3). Overall, waste gas and solid waste have increased over time, although wastewater discharge has been on a downward trajectory since 2005. Similarly, emissions of major pollutants (e.g., NH_4^+, SO_2, and NO_x) changed from an upward to downward trend during 1978 to 2016.

For the purpose of illustrating the relationship between economic growth (GDP) and environmental impact, a "decoupling index" (DI) was applied (Supplementary Materials) (*3*, *18*–*20*). By applying the DI metric to a number of environmental variables (Fig. 1A and fig. S2), industrial wastewater discharge reflected an increasing load trend from 1978 to 1995 (ranging from 22,639.46 to 37,285.08 million tons) with DI > 0 (the rate of growth in pollutant emissions falls short of economic growth), and then a decreasing trend from 2005 to 2016 (24,311.21 to 18,640 million tons) with DI < 0 (pollutant emissions decrease while the economy keeps growing), which represents the transformation from coupling to decoupling of GDP increase and environmental impact. Industrial waste gas and solid waste discharge also highlight a clear coupling with the growing economy from 1978 to 2011, which has stabilized or even shown a slight downward trend in recent years, with DI falling to zero or even lower. The major pollutants from wastewater and waste gas show a clear transformation from coupling to decoupling with economic growth (fig. S2). Since 2007, China has implemented a national strategy of energy conservation with much tighter emission limits (*18*); thus, SO_2, NO_x, and smoke dust emissions have declined by 75, 50, and 42%, respectively, in recent years. However, DI of CO_2 emissions was consistently >0 from 1979 to 2016, indicating a strong coupling with economic development. Energy consumption has increased six-fold from 1978 to 2016 (fig. S1H), and China has become the world's top energy consumer and CO_2 emitter, accounting for 30% of the global carbon emission (*21*–*23*).

DI only indicates the coupling or decoupling state between single environmental variables and economic growth (GDP). To present the correlation between economy and integrated environmental variables, we applied a coupling model (Supplementary Materials). As shown in Fig. 1B, the level of coupling exhibited an increasing trend from 1978 to 2002, was stable from 2002 to 2014, and then trended downward in 2015, indicating that since 2015, economic growth and environmental impact have shown a decoupling response. Related studies on environmental Kuznets curves also revealed that the turning point for SO_2 emission was found in 2015 (*24*), while the turning point for CO_2 has not yet been reached, although this may happen by 2030 (*25*), and a variety of global models suggest that China's CO_2 emissions should peak during 2020 to 2025 to achieve the 2°C target by the end of 2100 (*26*, *27*). Policies to limit and manage environmental pressures and impacts have been crucial in the process

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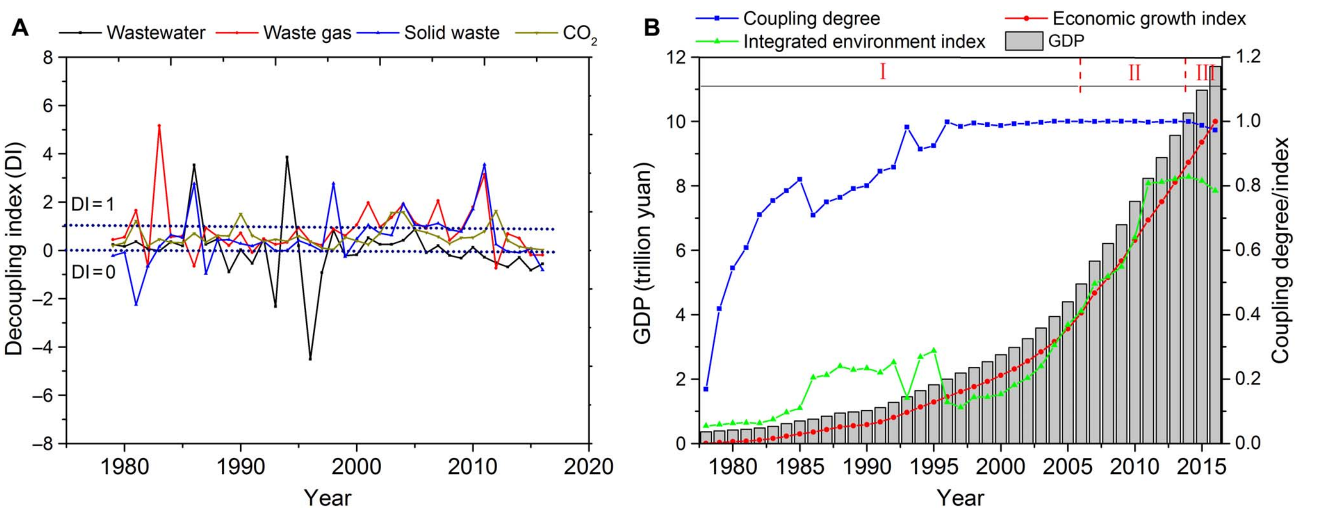

Fig. 1. Transformation from coupling to decoupling. (**A**) DI of wastewater, waste gas, solid waste, and CO_2 emission to GDP growth. (**B**) Variations of coupling degree between economy and environment. When DI ≥ 1, the rate of pollutant emissions keeps pace with or is higher than economic growth. When DI = 1, it represents the fulcrum point between absolute coupling and relative decoupling. When 0 < DI < 1, the rate of growth in pollutant emissions is less than that of economic growth. When DI = 0, the economy is growing, while pollutant emission remains constant. When pollutant emission decreases while the economy keeps growing, then DI < 0. Coupling degree calculation is described in the Supplementary Materials. I represents the ascending stage of coupling, II represents a stable stage of coupling, and III represents a descending stage of coupling. Data sources: China Statistical Yearbook (1979–2017) and China Statistical Compendium 1949–2014 (http://www.stats.gov.cn/english/).

of transformation. In 2012, the Chinese government proposed the concept of an "ecological civilization," which was made a national strategy. In addition, a revised Environmental Protection Law was enacted in 2015 (*28*) which tightened requirements to their strictest levels in China's history. Thereafter, a series of strict environmental protection policies were implemented, such as Action Plans for the Prevention and Control of Water, Soil and Air Pollution (*29*). The "13th Five-Year" Comprehensive Work Plan for Saving Energy, Controlling Greenhouse Gas Emissions, and Reducing Pollution set a series of emission reduction targets for SO_2, NO_x, COD, NH_4^+, and CO_2 from 2016 to 2020. Compared with 2015, emissions of SO_2, NO_x, COD, and NH_4^+ will reduce by 15, 15, 10, and 10% in 2020, respectively (*30*). Emission of CO_2 per GDP will reduce by 18% in 2020, and China's CO_2 emission will peak by 2030 (*31*). With the smooth implementation of these policies and action plans, sustainable decoupling between economic development and environmental impact is emerging.

Regional divide

Regional inequality since 1978 has been assessed using five key variables (*32*, *33*), namely, per capita GDP, disposable income, water resource consumption, energy consumption, and carbon emission.

Per capita GDP and disposable income

The Gini and Theil indexes were used to assess regional inequality in terms of per capita GDP in 31 provinces. The regional gap in equality narrowed from 1978 to 1990, then sharply diverged from 1990 to 1997, stabilized from 1997 to 2005, and then finally decreased since 2005 (fig. S4C). Previous studies have suggested that this pattern coincided with agricultural reform in the late 1970s and the 1980s, the beginning of opening up, a substantive input of foreign direct investment in the late 1980s and the 1990s, and the Chinese government development campaign for the western regions, which has been in place since the 2000s (*34*). Thirty-one provinces were divided into eight groups according to geographical and economic connections (fig. S4E). Initially, the reform and opening up policy was implemented in coastal regions, which led to development of a polarization between coastal and inland regions (Fig. 2A). Since 1987, performance of the east coastal region (including Shanghai, Jiangsu, and Zhejiang provinces) has outstripped other regions (fig. S4A). However, within each region, especially on the coast, infrastructure investment and rapid development achieved a degree of decentralization (fig. S4F). For example, the gap in performance between Zhejiang and Shanghai, and between Beijing and Tianjin narrowed. Recent policy preferences focused on the development of inland and western regions have slightly mitigated the provincial disparities since 2005 (Fig. 2A), while the rapid rise in performance of some provinces, such as Inner Mongolia and Chongqing, has expanded the subsequent development gap within the Central Yellow River and Southwest regions (fig. S4F).

Slightly different from GDP, the inequality in per capita disposable income doubled from 1978, reaching the highest from 1995 to 1997 and subsequently declining after 2005 (fig. S4D). This disparity of disposable income continued even when there was mitigation of the regional development gap. Governmental infrastructure investment and policy for stimulating the development of western regions since the 2000s were considered to have narrowed the development gap; however, the established wealth imbalance did not ease (*32*). A significant wealth gap mainly exists between coastal and inland regions, and the regional differences have changed over 40 years (fig. S5A). During the 1970s, with government subsidies, northwest regions including Tibet and Gansu had the highest per capita disposable income. Since the 1980s, the income level of Guangdong and Shanghai has grown rapidly and is now the highest in China. Since the 2000s, the provinces with relatively high per capita disposable income levels have been distributed along coast.

This significant gap is believed to be driven by historical and geographical factors, and is amplified by critical issues such as foreign investment, institutional bias, and region-specific development strategies (*32*, *35*). However, the incremental institutional change that started from several coastal cities and then extended nationwide is a key factor in achieving successful national reform, where best practice principles have been transferred and implemented in other geographical contexts.

Water resource consumption and availability

Total water consumption has increased by 9% since 2004 and slightly decreased since 2013, reflecting a similar decoupling trend (fig. S6A)

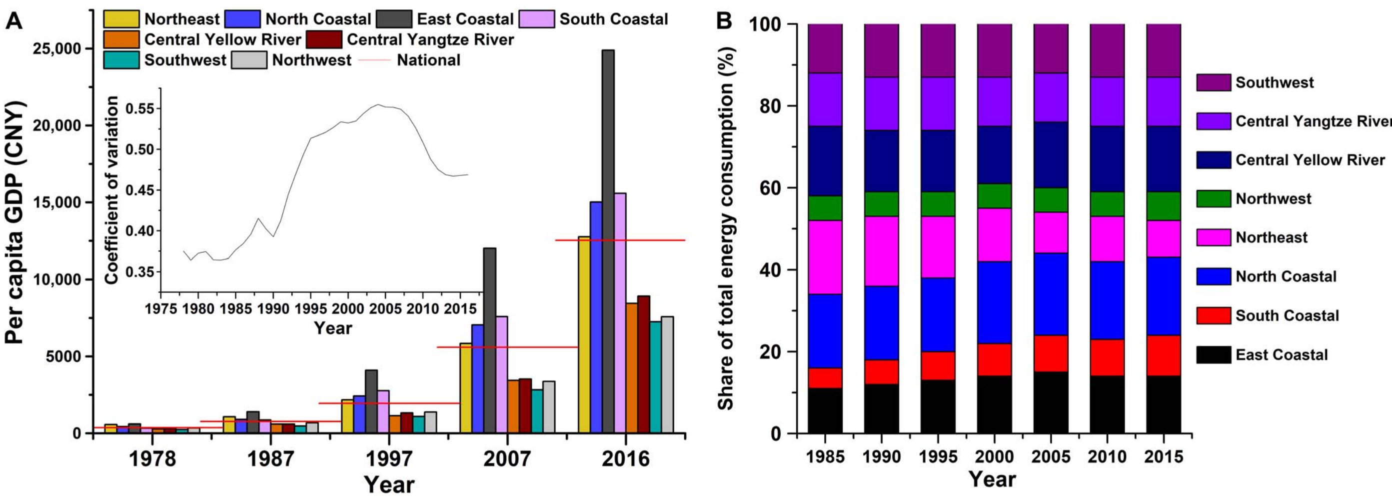

Fig. 2. Regional divide in per capita GDP and energy consumption. Regional divide in (**A**) per capita GDP and (**B**) percentile energy consumption of eight economic regions. The regional divide in GDP grew sharply between 1990 and 2005. It then decreased until recently when it began an upward trend. The contribution to total energy consumption of south and east coastal regions increased, while that of the northeast region, the old industrial zone of China, decreased from 1985 to 2015. Data sources: China Statistical Yearbook (1979–2017) and China Statistical Compendium 1949–2014 (http://www.stats.gov.cn/english/). Higher coefficient of variation indicates larger differences between regions.

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of pollutant emission and economy. Showing a different pattern from GDP and income level, per capita water consumption was highest in the northwest region followed by the east and south coastal regions (fig. S6B). The north coastal region is characterized by a large water deficit with a large population density (fig. S5B). Because water availability is less than water demand, the region has been forced to increase water use efficiency. Since 2010, the shortage of water resources in north China has been mitigated (fig. S5B), which may be attributed to both improved water-use efficiency and the implementation of the "South-to-North Water Diversion" national project.

Energy consumption and carbon emissions

The percentage of total energy consumption of coastal regions has increased from 34 to 43% since the 1990s, while that of the northeast region decreased significantly (Fig. 2B). Even with the already highlighted economic gap between coastal and inland provinces, the differences in per capita energy consumption did not continue to diverge, except that the per capita energy consumed in the northwest region increased rapidly and reached a peak in 2011 (fig. S6C). The inequality of per capita carbon emissions increased from 1997 to 2008 and then decreased after 2009. Since 2012, per capita carbon amounts from three major emitters—the northeast, north coastal, and central Yangtze River regions—have decreased and become decoupled from economic growth, while per capita carbon emissions of the northwest and east coastal regions have continued to increase (fig. S6D). In general, the northern and coastal regions have higher carbon emission rates than the southern and inland regions. The unequal carbon emissions are most likely influenced by the economic development level, economic structure, energy mix, and technological level (*36*).

Rural-urban gap

Economic reform in China has changed the population distribution between urban and rural areas, which has brought about a geo-specific gap in income, education, and health care. China's population increased from 0.96 billion in 1978 to 1.38 billion in 2016, with the contribution of urban population increasing from 20 to 60% due to the rapid urbanization process (*14*).

Employment and income

In 1978, the Household Contract Responsibility System was expanded across China, with the aim of improving agricultural productivity (fig. S7A). Surplus labor in the countryside was attracted by emerging employment opportunities in urban areas brought about by the development of the commodity economy (fig. S7B). Since the early 1990s, a progressive market system has further promoted economic growth, and the income of both the urban and rural people increased by more than 10-fold. However, the income gap between these two communities has also increased. The urban/rural (U/R) ratio for per capita income has been around three since 2003 (Fig. 3).

Four special economic zones, including Shenzhen, Xiamen, and Shantou, were established in 1979, and 14 coastal cities, including Qingdao in 1984, were chosen as the pilots for economic reform, highlighting the impact of economic and policy support, but they have shown different performances to date. Shenzhen is now one of the most developed cities in China, comparable with Beijing and Shanghai: Its income is far above the national average. Notably, Shenzhen became the first fully urbanized city in China in 2004, developing from a small fishing village in 1978. For Xiamen, Shantou, and Qingdao, the income gap between urban and rural areas is smaller than the national average, with U/R ratios for the three cities over the last 3 years of 2.4, 1.9, and 2.2, respectively. The stronger economic performance of their rural

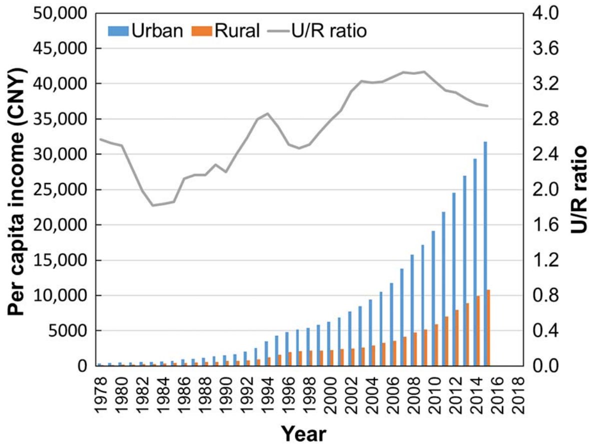

Fig. 3. Rural-urban gap of per capita income in China from 1978 to 2015. The income of both urban and rural residents has increased more than 10-fold since the 1990s, while the income gap has also increased. The U/R ratio for per capita income has hovered around three since 2003. The U/R ratio is defined as urban income divided by rural income to reflect the income gap. Data sources: China Compendium of Statistics 1949–2014 and China Statistical Yearbook 2017 (http://www.stats.gov.cn/english/).

neighborhoods might also explain the smaller gap in U/R productivity compared with other regions (fig. S7, C to F).

Education

Economic prosperity has enhanced education in China. The number of years of schooling for urban residents has increased from 8 to 13 and increased from 4 to 10 for rural residents. However, the urban-rural gap for education is not getting smaller, as there is a constant gap of 3 years (fig. S7G), and the current level of educational attainment in rural areas is the same as that in cities in the early 1990s.

A successful college entrance examination was, and still is, perceived to be the most significant opportunity for young people to develop their careers, even to change their life tracks. Higher education is much more accessible for urban students than for rural ones (*37*). In 1978, 7% of urban middle school students entered universities and colleges, and the number has continued to increase, reaching 50% in 2018. However, this pattern is not reflected in rural contexts, with 0% attaining tertiary education success in 1978 and only 7% in 2017 (fig. S7H).

Health care

Economic development has significantly improved human health, including childbirth and disease control (*38*). As for childbirth, the infant mortality rate dropped from 1.7 to 0.4% in urban areas and from 5.8 to 0.9% in rural areas (fig. S7I). At the same time, the maternal mortality rates of urban and rural mothers both declined and have now achieved parity at the same level of 2 per million (fig. S7J). Further, the urban-rural gap in childbirth rate is narrowing with time.

Major diseases and their crude mortality rates for rural and urban population have also been decreasing. In 1990, the most frequent fatal diseases for urban residents were recognized as cancer, cerebrovascular disease, and heart disease, and death rates for these were higher than those of rural residents. At the same time, rural residents suffered higher levels of respiratory disease (16‰) and overall mortality was nearly twice that of urban residents (9.2‰). In recent years, both rural and urban residents have been facing similar levels of cancer and cerebrovascular disease and increasing heart disease (fig. S7, K and L). Environmental pollution has been a major contributing

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factor to morbidity and mortality in China (*39*). Urbanization has generally reduced levels of cardiovascular activity of residents, and this, along with changes to diet, has had profound implications for disease incidence (*40*).

Social inequality

To measure the social heterogeneity and inequality in different groups (*41*), we chose three social evaluation indices, namely, gender equity in education, poverty reduction, and migration for employment.

Gender equity in education

In general, the education level for both genders has greatly increased. Since the early 1990s, the mean years of schooling in China have risen from 6.3 to 9.1. From a gender perspective, a female's number of years of schooling equated to 92.7% of that received by a male in 2016 compared to just 77.3% in 1991 (fig. S8A). Similarly, the gap in mean years of schooling between male and female in all provinces has continued to decrease (Fig. 4 and fig. S8B). This is consistent with the reported result that gender inequality in education decreased significantly during the past decades in China (*42*).

Migration for employment opportunities

The migrant population in China increased slowly in the 1980s, but increased rapidly from the early 1990s to 2015, and exceeded 100 million people by 2000 and 200 million people by 2008. However, since 2015, a small decline has occurred in the total migrant population, as some migrant people have become newly registered citizens of both small- and medium-sized cities (fig. S8C). With large numbers of people flowing into cities, the urbanization rate of China rose from 17.92% in 1978 to 57.35% in 2016. Since 1996, the urbanization rate has risen sharply, with an average of about 21 million people becoming new permanent urban residents every year (fig. S8D). Migrant workers mostly move from the central to east regions of the country (fig. S9A). A historic household registration system in China restricted the movement of population from one region to another for a long time. In recent years, reforms in the identity card and residential permit systems have been more conducive to the migration of the population between regions and cities. In addition, people have improved employment opportunities by moving to richer regions (*43*).

Poverty reduction

In 1978, more than 700 million people lived below the poverty line (100 CNY per year), but now, only 43 million people live on under 2300 CNY (constant 2010) per year (fig. S8E). Poverty incidence in rural China has dropped sharply from 97.5% in 1978 to 4.5% in 2016 (national line 2010) (fig. S8E). According to the World Bank, the poverty headcount ratio at $1.90/day [2011 purchasing power parity (PPP)] in China has dropped sharply from 66.6% in 1990 to 0.7% in 2016 (fig. S8F). This drop reduced the number of those living in extreme poverty to about 9.6 million in 2016. The Chinese government has carried out a significant number of large-scale poverty eradication programs (*44*). The number of Chinese citizens moving out of poverty accounts for 70 percent of the world's total from 1990 to 2015 (*45*). The spatial distribution of the population living below the poverty line is extremely uneven. The eastern region has less of its population living below the poverty line, while the western region has a higher poverty incidence (fig. S9B). In addition, as rural residents move to urban areas, the urban employment market has become competitive and some urban residents, therefore, face the challenge of a fall in living standards (*46*).

Integrated land-ocean development

For a long time, more attention has been paid to the goods and services delivered by terrestrial ecosystems (*8*), and the surrounding ocean area has not even been considered by many as a part of the total homeland area. China, with vast maritime territory (3 million km^2) and long coastline (32,000 km), has abundant marine resources that provide enormous opportunity for development. The sufficiency and sustainability of using the oceans, seas, and marine resources for sustainable development have been measured using data on gross marine product (GMP), land-based pollution, and ecological health.

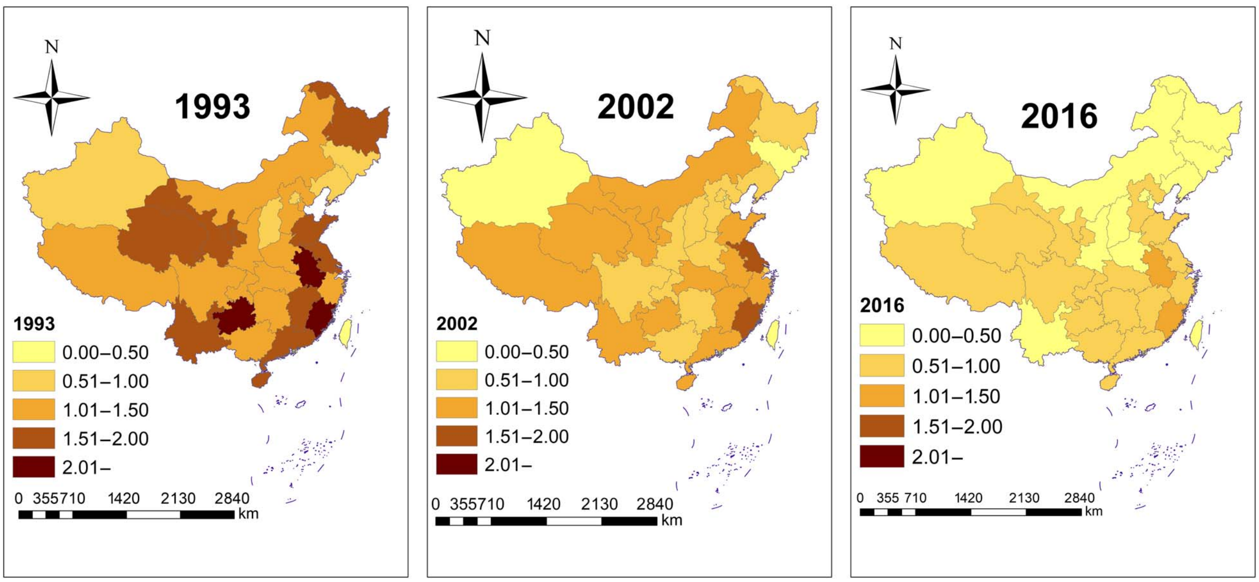

Fig. 4. Social inequality: Gap of the mean years of schooling between males and females in different provinces (unit: year). During the past decades, the gender gap of the mean years of schooling in different provinces decreased significantly. The gender gaps of the mean years of schooling were less than 1 year for most of the provinces in 2016. Note that the data were derived from China Population and Employment Statistics Yearbook (1994–2017).

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Sufficiency of ocean economy

Marine economy has become an important focus of China's economy but is still poorly developed as a sustainable economic sector. China's marine industry has diversified, and the number of marine industries recently increased (*47*). Although GMP (*8*) grew steadily from less than 4 billion CNY in 1979 to 7761 billion CNY in 2017 (Fig. 5), the contribution of GMP to GDP was only 9.4% in 2017, which is much lower than the contribution of sea area (about 24%) to the total jurisdiction. In 2017, the GMP per square kilometer of water area was 2.6 million CNY, which was one-third of that on land. Internationally, the labor productivity of marine industries for China (209,250 CNY per employee in 2017) was far below that for the United States [762,750 CNY per employee in 2014 (*48*)]. Taking into account the possibility that the GMPs were overstated as a result of exaggerated reported fisheries catches (*49*), the gap could be much larger.

Pressures from human activities

According to China Fishery Statistical Yearbooks, China's total production of domestic marine-caught and farmed fish had shown annual growth of 6.35% in weight from 1990 to 2017. Aquaculture expansion caused an increasing dependence on wild fish, from China and other countries, used as feed (*50*). Not only has the unsustainable exploitation of marine resources affected the marine economy but land-based activities have also played a great role. Land-based activities are inherently affecting the blue economy, which directly or indirectly affects people's livelihoods and well-being since the world depends on resources from the ocean. Dumpling of unwanted terrestrial waste into the ocean (*51*), including point and nonpoint sources of pollution (from agriculture and mining) directly or indirectly affect the marine environment. The amount of industrial wastewater discharged directly into the sea has increased from an average 0.7 billion tons every year in the 1990s to an average 1.2 billion tons every year in the 2010s (fig. S10A). The density of floating garbage on the ocean recognized as being discharged from land-based sources has also increased from 6.3 kg/km^2 in 2010 to 43.6 kg/km^2 in 2016 (fig. S10B). China's total coastal reclamation area was found to be 7500 km^2 between 1985 and 2010 (fig. S10C) (*52*).

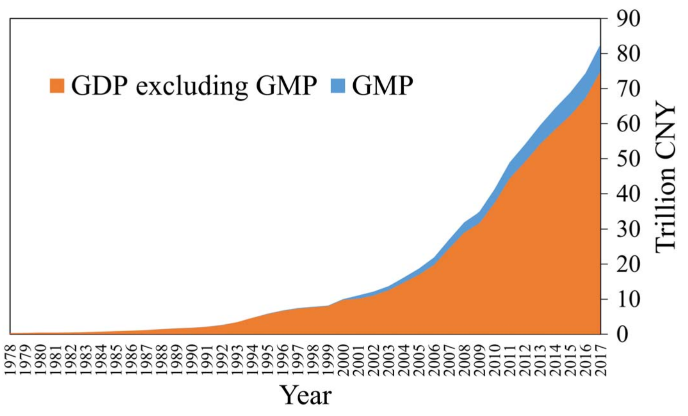

Fig. 5. Toward integrated land-ocean development: Contribution of GMP to the GDP, 1978–2017. Marine resources remain underexploited in the context of economic growth. Note that for 1986–1992, the marine economy was defined as the output value of major marine industries. Data sources: China Marine Statistical Yearbook 1993, 1997–2016; Statistical Communique of Chinese Marine Economy 2017; and China Statistical Yearbook 1979–2017 (http://www.stats.gov.cn/english/).

Impacts on marine ecosystem health

Consequently, human activities such as aquaculture expansion, pollution, and reclamation have affected marine ecosystem health. These activities have caused significant loss of ecosystem services (*53*, *54*), which then affects the sustainability of the ocean economy and of the world at large (*55*, *56*). Because of synergistic effects of climate change and pollution, the occurrence of red tides increased from an average of 25 times every year in the 1990s to 57 times every year in the 2010s (fig. S10D). Aquaculture expansion was at the cost of reduced species diversity (*57*, *58*). The region-based marine trophic index and mean maximum body length of the catch has decreased sharply since the early 1980s, implying an increasing catch of organisms with low trophic level. Although they increased gradually after the implementation of the Fishery Law of the People's Republic of China in 1987, these two indicators were still lower than that in 1978 (fig. S10E). China's fisheries management mainly relies on technical and input control measures, such as minimum mesh size regulation and seasonal fisheries closure. This, however, is an incomplete management strategy (*59*). To enhance sustainability, China should further advance marine development through innovative science and technology and pay more attention to strengthening the enforcement of conservation policies.

DISCUSSION

Insights from China's transition toward a sustainable path

In summary, China's reform was first inspired by a small group of farmers struggling for basic well-being, which was gradually recognized and endorsed by the government at all levels. Subsequent "opening up" was piloted in a few coastal cities, and then their experiences were shared nationwide. It has been both a bottom-up and top-down process. The greatest success of the reform has been institutional change and appropriate policy reform.

Between 1978 and 2015, with DI > 0, China's economic prosperity was coupled with pollutant emissions and loss of natural capital. However, since 2015, the relationship has weakened with DI < 0 as a result of a series of environmental reform actions. There continues to be a geographical divide in economic prosperity, resource consumption, and emissions between some regions, but this gap has been reduced incrementally. An urban-rural divide in disposable income and education levels is unchanged, while the gap in human health and welfare has reduced significantly. Urban populations have three times the disposable income and three more years of schooling than rural populations, but both groups can now receive the same level of health care (in terms of child birth mortality and disease control). The national education attainment level has increased significantly, and the gap in years of schooling between genders has been narrowed. In recent years, reforms in the household registration system have been more conducive to population migration, and annually, more than 200 million migrants aid economic development and help reduce the regional gap and urban-rural divide. The land-based economy has been the dominant driver of change, but the potential for maritime development cannot be underestimated, and more attention should be given to diversification of marine resource use and an integrated land-sea management system.

China's growth is reflected in positive outcomes for the UN SDGs, such as reducing poverty (SDGs 1 and 2) and increasing employment opportunities (SDGs 8 and 11) (by promoting population migration and urbanization) and economic growth (SDGs 8 and 9). Further, substantial progress has been made in improving health and welfare

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(SDG 3), reducing gender inequality (SDG 5), and even toward eliminating the gender disparity in education (SDG 4), which is a key indicator of sustainable prosperity. The decoupling of economic growth and pollutant emissions (SDGs 7 and 13) has been supported through the development of national policy to address natural resource management and the further restoration and remediation of historical pollution impacts particularly around water (SDG 6), biodiversity (SDG 15), and marine ecosystems (SDG 14).

The opening up policy has enabled China to learn from other countries, either developed or developing. To strengthen its own capabilities, China has expanded research capacity, emphasized advanced management and increased infrastructure development. China has entered a new stage of development, with growth rate of domestic investment on infrastructure development decreasing and rapidly increasing foreign investment. China has also expanded its foreign direct investment through such international programs as the "Belt and Road Initiative" to promote economic cooperation, technological innovation, and resource sharing between regions and countries. On the basis of its own national conditions, China has taken a "small step, but fast run" rather than a "shock therapy" approach, with new policies or programs. This was first demonstrated on a small scale, and then incrementally spread to the whole country, to ensure success and reduce the trial-and-error cost as far as possible. China has increasingly realized the importance of achieving an "ecological civilization" by learning from the past and promoting an aggressive decoupling of the relationship between environmental pollution and associated loss of natural capital and economic growth, and chosen to make sustainable development a national strategy.

However, China still faces major challenges in carbon emission (SDG 13), pollution control (SDGs 6 and 15), income inequalities (SDG 10), urban-rural gap (SDGs 4 and 11), and marine ecosystem (SDG 14). There is a long way for China to go toward the delivery of sustainable development goals. Reform and opening up should continue to be further reinforced by enhancing environmental protection, land-ocean integration, regional equity, and social equality.

MATERIALS AND METHODS

A series of economic, social, and environmental indicators, which were measured by the latest published data with a unified statistical adjustment to ensure comparability, were used to reflect the development of China in the past 40 years (Supplementary Text). A DI and coupling model were used to illustrate the relationship between economic growth and environmental impacts. When selecting environmental variables, the representation and severity of the environmental problems and degree of public concern were considered. To assess the regional disparity, Theil and Gini coefficients were used. All the methods were specified in the Supplementary Materials. For the convenience of comparison, CNY was used with the average exchange rate in 2017 (USD:CNY, 1:6.75). Spatial analysis was performed for 31 provinces excluding Hong Kong, Macao, and Taiwan due to data unavailability, with Arcmap software in ArcGIS version 9.3. Data were collected from national, provincial, and municipal statistical databases, including the China Statistical Yearbook, China Compendium of Statistics 1949–2014, the China Marine Statistical Yearbook, China Energy Statistical Yearbook, and China Population and Employment Statistical Yearbook.

Constant GDP

To present the actual economic development, we used the GDP index to calculate the constant GDP by taking 1978 as the base year. The equation for calculating the constant GDP was as follows

$$V_i = V_{ipresent}/D = V_{1978}\cdot A_i = V_{1978}\cdot\prod_{978}^{i} a_i \quad (1)$$

where V_i is the constant value of GDP in year i, $V_{ipresent}$ is the current value of GDP in year i, D represents the deflator index, A_i is the GDP index of year i on the base year (1978), and a_i is the GDP index of year i on the previous year (i − 1).

To present the actual purchasing capability, disposable income is adjusted to 1978-based value by using the consumer price index instead of A_i.

CO_2 emissions

In this study, we estimate fossil fuel–related CO_2 emissions by energy types (*23*, *60*)

$$\mathrm{CE}_i = \mathrm{CD}_i \times \mathrm{EF}_i \quad (2)$$

where CE_i is the CO_2 emission from energy i, CD_i is the consumption of the ith energy (metric tons), and EF_i is the emission factor for energy i (*22*, *60*).

By summarizing the emissions from different energy types together, we obtain the total CO_2 emissions in Eq. 3

$$\mathrm{CE} = \sum \mathrm{CE}_i \quad (3)$$

Decoupling index

DI refers to the ratio of (i) change in the rate of a given pollutant emission (e.g., SO_2) and (ii) change in the rate of economic growth (GDP) within a certain time period (typically 1 year). For example, if we define $\Delta P_t = P_t/P_{t-1}$ (pollution emission) and $\Delta Y_t = Y_t/Y_{t-1}$(economic growth), then the DI in year t: DI = $\Delta P_t/\Delta Y_t$. When DI ≥ 1, it means that the increasing rate of pollutant emissions keeps pace with or is higher than economic growth; when DI = 1, it is the turning point between absolute coupling and relative decoupling; when 0 < DI < 1, it means that the rate of growth in pollutant emissions falls short of that of economic growth; when DI = 0, it means the economy is growing, while pollutant emission remains constant; when pollutant emissions decrease while the economy keeps growing, then DI < 0.

Coupling degree

The required data about economic indicators and environmental indicators were collected from the China Statistical Yearbooks (1979–2017). Here, GDP was used as an economic indicator, and total emissions of wastewater (A), waste gas (B), solid waste (C), and CO_2 (D) were used as environmental indicators. We standardized the data using Eq. 4 and eliminated the influence of dimension and magnitude

$$X'_{ij} = (X_{ij} - \min\{X_j\})/(\max\{X_j\} - \min\{X_j\}) \quad (4)$$

where X_{ij} represents the value of indicator j in year i, and $\max\{X_j\}$ and $\min\{X_j\}$ indicate the minimum and maximum values of indicator j among all years.

To determine the weight of each indicator in the economic-environmental indicator systems, we used the entropy method (*61*, *62*). The weight of each indicator was calculated according to information entropy and variations in the indicators. The detailed steps for

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calculating the weight of each indicator were as follows (Eqs. 5 to 8) (where n is the number of indicators, and m denotes years):

The proportion of the indicator j in year i

$$Y_{ij} = X'_{ij} / \sum_{i=1}^{m} X'_{ij} \tag{5}$$

Information entropy of the indicator j

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} Y_{ij} \times \ln Y_{ij} \; 0 \leq e_j \leq 1 \tag{6}$$

Entropy redundancy

$$d_j = 1 - e_j \tag{7}$$

Weight of the indicator

$$w_j = d_j / \sum_{j=1}^{n} d_j \tag{8}$$

Evaluation of a single indicator

$$S_{ij} = w_j \times X'_{ij} \tag{9}$$

Economic growth index in year i

$$S_{i\text{GDP}} = w_{\text{GDP}} \times X'_{i\text{GDP}} \tag{10}$$

Integrated environment index in year i

$$S_{i\text{E}} = \sum_{j=1}^{n} S_{ij} = S_{i\text{A}} + S_{i\text{B}} + S_{i\text{C}} + S_{i\text{D}} \tag{11}$$

where $S_{i\text{GDP}}$ is the economic index, $S_{i\text{E}}$ is the integrated environment index, $S_{i\text{A}}$ is the wastewater emission index, $S_{i\text{B}}$ is the waste gas emission index, $S_{i\text{C}}$ is the solid waste emission index, and $S_{i\text{D}}$ is the CO_2 emission index. Here, the greater the value of $S_{i\text{GDP}}$, the faster the economic development, and the greater the value of $S_{i\text{E}}$, the greater the environmental pressure.

Coupling describes the phenomenon by which two or more systems influence each other through interactive mechanisms. While the concept has been widely applied in research addressing climate change, it has seldom been used to further understand the relationship between economy and environment (*61*). The model for assessments of the coupling relationships is developed as follows

$$C = \{(m_1 m_2 \cdots m_n)/[\Pi(m_i + m_j)]\}^{1/n} \tag{12}$$

Because of similarities in the coupling relationship between quite different systems, coupling is considered appropriate in studying the relationship between economy and environment, despite its origins in physics. The coupling degree model for economy and environment can be written as

$$C = \{f(E_1)g(E_2)/([f(E_1) + g(E_2)]/2)^2\}^{1/2} \tag{13}$$

where C is the coupling degree of economy and environment, $f(E_1)$ is the economic system, and $g(E_2)$ represents the environmental system.

Theil index

$$\text{T} = \sum p_i \ln\left(\frac{\overline{\text{GDP}c}}{\text{GDP}c_i}\right) \tag{14}$$

where $\text{GDP}c_i$ is the per capita GDP of province i, $\overline{\text{GDP}_c}$ is the average per capita GDP of all provinces, and p_i is the share of province i to the total national population.

Gini coefficient

Gini index using the general calculation

$$G = \frac{1}{2\mu n^2} \sum\sum |x_i - x_j| \tag{15}$$

where X_i is the attributes of the ith province selected to discuss, μ is the national average of this attribute, and n is the number of samples.

Mean years of schooling

First, we assume that primary school level is 6 years, junior high school level is 9 years, high school level is 12 years, and college and above level is 16 years. Then, the mean years of schooling is given by the formula

$$MYS = \Sigma(P_1{*}6 + P_2{*}9 + P_3{*}12 + P_4{*}16) \tag{16}$$

where P_i is the population rate with education level i.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/5/8/eaau9413/DC1

Fig. S1. Economic growth, total emissions of waste gas, wastewater, solid waste and CO_2, and the major pollutant emission in waste gas, wastewater, and solid waste in China from 1978 to 2016.
Fig. S2. DI of wastewater, waste gas, solid waste, smoke and dust, SO_2 emission, and CO_2 emission to GDP growth.
Fig. S3. Spatiotemporal variations of waste gas, wastewater, and SO_2 emission in China.
Fig. S4. Regional divide in per capita GDP and disposable income.
Fig. S5. Spatiotemporal variation of per capita disposable income and water deficit of 31 provinces.
Fig. S6. Regional per capita water and energy consumption.
Fig. S7. Rural-urban gap in employment, income, education, and health care in China, 1978–2017.
Fig. S8. Indices for gender equity in education, migration for job opportunities, and poverty reduction.
Fig. S9. Spatial analysis for indices of migration for job opportunities and poverty reduction.
Fig. S10. Marine fish catch and land-ocean interactions.

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