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Emission inventory and trends of NO_x for China, 2000–2020*

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Abstract: The rapid growth of NO_x emissions in China is mainly due to intensive fossil fuel consumption. In order to control NO_x emissions, a multiyear NO_x emission inventory was established by a bottom-up approach for the period 2000–2010. The results showed that NO_x emissions increased by 2.1 times from 11.81 million tons (Mt) in 2000 to 24.33 Mt in 2010. We found that NO_x emissions had exceeded SO_2 emissions in 2009 by comparison with their emission trends. We also found that the unbalanced NO_x emissions in Eastern China and Western China are mainly due to the different gross regional product and industrial structure. Accounting for 70% of total energy consumption in China, coal is the largest NO_x emission source among all the fossil fuels. In addition, the increased use of diesel and gasoline has spurred the increase of NO_x emissions from the transportation sector. Manufacturing, electricity production, and transportation together composed about 90% of the national NO_x emissions. Meanwhile, energy consumption and NO_x emissions in China are predicted to be 3908.5 Mt standard coal equivalent (SCE) and 19.7 Mt in 2020 with this scenario analysis, respectively. To achieve a desired NO_x reduction target, China should take strict measures to control NO_x emissions, such as improvement in reduction technology, promulgation of new emission standards, and joint control by various Chinese provinces.

Key words: NO_x, Emission inventory, Scenario prediction, Energy consumption, China
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1 Introduction

Anthropogenic nitrogen oxides, mainly from the consumption of fossil fuels, have a series of complicated influences on tropospheric chemistry, leading to phenomena such as summer photochemical smog (Dimitriades, 1972; Rubio *et al.*, 2002), the increase in urban and tropospheric ozone levels (Volz and Kley, 1988; Melkonyan and Wagner, 2013), acid deposition (Galloway, 1995; Sickles and Shadwick, 2007; Matsumoto *et al.*, 2011), and the formation of nitrate aerosol (Kim *et al.*, 2012). These are major concerns for ambient air quality and have broad impact on human health (Weschler, 2006). Due to the rapid growth of the economy between 2000 and 2010, China became the second largest economy in the world and experienced a rapid increase of energy consumption, which directly spurred the increase of NO_x emissions. Consequently, China is the largest NO_x emission country in Asia contributing 41%–57% of Asian NO_x emissions (Streets and Waldhoff, 2000; Ohara *et al.*, 2007; Klimont *et al.*, 2009; Zhang *et al.*, 2009), and has been suffering from severe environmental pollution and public health problems (Zhang Q.Y. *et al.*, 2007; Kan *et al.*, 2012). To control NO_x emissions, a 10% cut of NO_x emissions by 2015 has been listed as an obligatory target in the 12th Five-Year Plan (FYP, 2011–2015) of China (MEP, 2011), on the basis of conditions that exist in 2010.

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To assess the impacts of NO_x emissions on the troposphere and to develop practical strategies for NO_x mitigation, detailed knowledge of emission loads, spatial environment and temporal distribution are required. Although several emission inventories for China have been established over the past decade (Streets and Waldhoff, 2000; Hao *et al.*, 2002; Ohara *et al.*, 2007; Zhang Q. *et al.*, 2007; Cao *et al.*, 2011; Saikawa *et al.*, 2011), they are either out of date or just cover a short period. In this work, we carried out a multiyear NO_x emission inventory by bottom-up approaches in China during the period 2000–2010, which described NO_x emission variation, and we analyzed the contributions of NO_x emissions by different fossil fuels, provinces, and economic sectors. The NO_x emission trends over the period 2011–2020 are predicted by using scenario analysis approaches, and then some suggestions on sustainable development and NO_x emission control are proposed.

2 Analysis methods and data sources

2.1 Bottom-up method

The NO_x emissions estimated by bottom-up methods in this research only come from fossil fuel consumption from different economic sectors in China, including coal, coke, crude oil, gasoline, kerosene, diesel, residual oil, and natural gas. Gschwandtner *et al.* (1986) described the concept of the bottom-up method that we applied here. Our estimate of NO_x emissions for China was developed with the widely used equations as given below (Hao *et al.*, 2002; Streets *et al.*, 2006; Klimont *et al.*, 2009; Zhang *et al.*, 2009):

$$E_{Ty} = \sum_i E_{iy}, \tag{2-1}$$

$$E_{iy} = \sum_j E_{ijy}, \tag{2-2}$$

$$E_{ijy} = \sum_k A_{ijky} \sum_m \left[\mathrm{ef}_{jkmy} X_{ijkmy} \right], \tag{2-3}$$

$$\mathrm{ef}_{jkmy} = \mathrm{ef}_{jk}(1 - R_{jkmy}), \tag{2-4}$$

where T represents the national NO_x emissions of China, y represents the year, i represents the province, j represents the economic sector, k represents the fuel type, m represents the emission reduction technology type, E is China's NO_x emissions calculated as NO_2, A is the activity levels, such as fuel consumption, ef is the emission factor weighted as NO_2, R is the removal efficiency of the emission reduction technology, and X is the fraction of fuel for a sector j that is consumed by a specific technology m.

2.2 NO_x emission factors of China

As China has promulgated a series of improved national emission standards for coal-fired power plants, industrial boilers, and vehicles, the NO_x emission factors in China varied over the period 2000–2010. By selecting the appropriate emission factors, we multiplied the uncontrolled emission factors by removal efficiency, which is described in Eq. (2-4). The removal efficiency was valued as 20%–40% from 2000 to 2010 with an annual average growth rate, based on Hao *et al.* (2002) and the National Development and Reform Commission of China (NDRC, 2013). Emission factors for different economic sectors and fuel types are derived from a wide range of sources as summarized in Table 1.

Table 1 NO_x emission factors* (kg NO_2/t)

Fuel type	NO_x emissions				
	Industry	Electricity	Transportation	Domestic use	Others
Coal	2.38–7.50	4.00–11.80	7.50	1.19–2.24	3.75
Coke	9.00		9.00	2.25	4.50
Crude oil	3.35–7.26	2.10–10.60	5.09	1.70	3.05
Gasoline	16.70	2.10–16.70	15.00–58.20	16.70	16.70
Kerosene	7.46	21.20	27.40	2.49	4.48
Diesel	9.62	2.10–8.54	13.24–58.20	3.21	5.77
Residual oil	5.84	2.10–10.06	27.40–54.10	1.95	3.50
Natural gas**	20.85–27.14	17.27–55.67	20.85	14.62	14.62

*These emission factors were summarized from (Hao *et al.*, 2002; Streets *et al.*, 2003; Ohara *et al.*, 2007; Klimont *et al.*, 2009; Zhao *et al.*, 2010; Wang *et al.*, 2011); **Emission factors are in kg NO_2/t, except for values of natural gas, which are in 10^{-4} kg NO_2/m^3

2.3 Activity levels of China and analysis uncertainty

The scope of the inventory includes all the administrative regions of China, except Hong Kong, Macau, and Taiwan, due to the lack of available data. Fossil fuel consumption data from each economic sector (including manufacturing, electricity, transportation, construction, domestic use, and others) and each province in the period 2000–2010 was obtained from the National Bureau of Statistics of China (NBS, 2000–2012), and the China Energy Statistical Yearbook (CESY) (DESNBS, 2000–2010). The accuracy of NO_x emission estimates mainly depend on activity levels, source categories and emission factors. Due to the difficulty in data collection on energy consumption of small boilers, and emission factors in the manufacturing sectors, such as cement production, uncertainties may be introduced into the NO_x emission inventory. The uncertainties of a bottom-up emission inventory of NO_x in China have been comprehensively quantified by Zhao *et al.* (2011), who suggested that the uncertainties (95% confidence intervals around central estimates) of Chinese NO_x emissions were estimated to be −13%–37%. In view of some arguments that the Chinese government probably underestimated the energy consumption during the period of 2000–2002 (Akimoto *et al.*, 2006), we also used energy consumption data from various relevant literature (Zhang Q. *et al.*, 2007; Zhao *et al.*, 2011) to reduce any uncertainties.

2.4 Method for projected emissions

In modern society, each human individual poses a negative impact on the environment. The total negative impacts can be expressed by the IPAT (I: environmental impact; P: population; A: affluence; T: technology) equation, which was proposed by Ehrlich and Holdren (1971). It is a simple conceptual expression that the factors, such as population, economic growth, and technological change, create an environmental impact. We use the IPAT variants Eqs. (2-5) and (2-6) to project the future energy consumption and NO_x emissions of China in different scenarios (Lu, 2009).

$$D_f = D_b(1+g)^{f-b}(1-t)^{f-b}, \tag{2-5}$$

$$B_f = B_b(1+g)^{f-b}(1-d)^{f-b}, \tag{2-6}$$

where b represents the base year, f represents the forecast year, g is the average annual growth rate of gross domestic product (GDP) between b and f, t is the average annual decline rate of energy consumption per unit of GDP between b and f, d is the average annual decline rate of NO_x emissions per unit of GDP between b and f, D is the amount of energy consumption, and B is the amount of NO_x emissions.

3 Results and discussion

3.1 Growth of NO_x emissions, energy consumption, and GDP, 2000–2010

Table 2 summarizes the annual NO_x emissions that were estimated by either bottom-up methods or top-down methods (satellite observation) in China for the period 2000–2010. The differences between our estimation and other researchers' were due to the utilization of different data sources. China's economy has been maintaining a dramatic growth rate since the late 1970s, accompanying with an increased use of fossil fuels. As a main pollutant from fossil fuel combustion, NO_x has caused many environment problems and its emissions are growing annually in China. Fig. 1 shows the growth trends of GDP, energy consumption (calculated as standard coal equivalent (SCE)), and NO_x emissions in China for the period 2000–2010. To rule out the impacts of alternative prices on environmental loads per unit of GDP in different years, GDP was calculated at constant prices for the year 2000. Chinese GDP increased dramatically by 2.7 times from 9921.4 billion CNY in 2000 to 27 095.6 billion CNY in 2010. At the same time, energy consumption in China grew by 2.2 times, which directly spurred the increase in NO_x emissions. As a

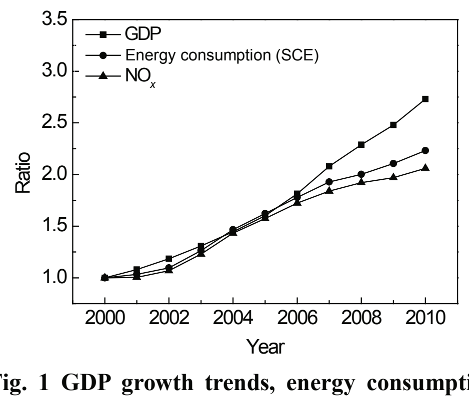

Fig. 1 GDP growth trends, energy consumption and NO_x emissions of China

Table 2 Annual NO_x emission estimation in China (Mt NO_2)

Reference	Sources	NO_x emission estimation										
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
NBS and MEP, 2010	FF+BF								17.98			22.74
Bottom-up methods												
Ohara *et al.*, 2007	FF+BF+BB	11.19	11.77	12.69	14.49							
Zhang *et al.*, 2007	FF+BF	12.60	13.20	14.40	16.20	18.60						
Klimont *et al.*, 2009	FF+BF+BB	11.65					16.93					
Cao *et al.*, 2011	FF+BF+BB								23.25			
Saikawa *et al.*, 2011	FF+BF+BB	11.75										
Zhao *et al.*, 2013	FF	12.00					19.48					26.05
This research	FF	11.81	11.86	12.62	14.53	16.92	18.59	20.35	21.72	22.69	23.26	24.33
Top-down methods												
Wang *et al.*, 2011	FF+BF						18.50					
Wang *et al.*, 2012	ALL						21.54	23.60	25.99	26.83		

FF: fossil fuel; BF: biofuel combustion; BB: biomass burning; ALL: FF+BF+BB+soil emissions+lightning

result, China's NO_x emissions increased rapidly by 2.1 times, increasing from 11.81 million tons (Mt) in 2000 to 24.33 Mt in 2010.

Both energy consumption and NO_x emissions per unit of GDP increased slightly in 2003, compared with those in 2002, as shown in Fig. 2. It can be explained by the fact that China had come out of the shadow of the Asian economic recession, and flung itself into another economic boom. The year-over-year growth rates for energy consumption and NO_x emissions in 2003 were 15.3% and 15.1%, respectively, which was higher than that of the GDP (10.5%). The secondary industry shares for the GDP of China increased from 49.7% in 2002 to 58.5% in 2003, which was the highest share during the period 2000–2010. With the boom of energy-intensive secondary industries, including electricity, construction, and manufacturing, the energy consumption and NO_x emissions increased significantly. However, in the long term, energy consumption and NO_x emissions per unit of GDP decreased by 18.2% and 24.7% for the period 2000–2010, respectively. This is because the Chinese government has introduced a number of energy conservation and emission reduction policies, which accelerated the industrial restructuring process over the past years. For instance, compared with the secondary industries, the tertiary industries are a well-accepted and environmental friendly industries, whose share of China's GDP increased from 39.0% in 2000 to 43.2% in 2010 (NBS, 2000–2012). These changes had a positive effect on reducing NO_x emissions.

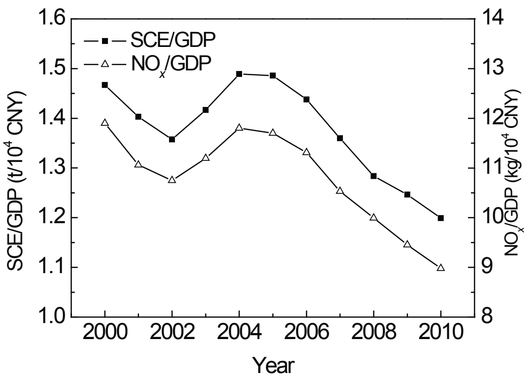

Fig. 2 Energy consumption and NO_x emissions per unit of GDP in China

3.2 Comparison of SO_2 and NO_x emissions

To control SO_2 emissions, flue gas desulfurization (FGD) technology has been widely implemented in coal-fired power plants in China due to its high efficiency and reliability. The FGD penetration rate in coal-fired power plants was approximately 86% in 2010 (Schreifels *et al.*, 2012). Therefore, the emissions of SO_2 have been under effective control as shown in Fig. 3 (NBS, 2000–2012). On the other hand, the NO_x emissions have increased over the past few years due to the lack of an effective control technology. It has been shown that NO_x emissions had exceeded SO_2 emissions in 2009, and the emission ratio of NO_x to SO_2 increased from 0.59 in 2000 to 1.11 in 2010 in China. This means that the achievements on curbing acid rain from reducing SO_2

emissions are compromised by the increase in NO_x emissions (Zhao *et al.*, 2009). In addition, the type of acid rain in China may convert from sulfuric dominant into nitric dominant. As NO_x can react with other pollutants to form a secondary pollution, such as photochemical smog and ground-level ozone, its impacts on the environment and human health may outstrip SO_2 in China. Hence, the Chinese government should pay more attention to improving NO_x emission control.

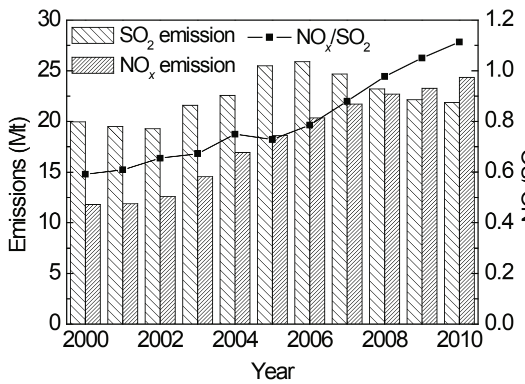

Fig. 3 Comparison of SO_2 and NO_x emissions in China

3.3 NO_x emission inventory of fossil fuels, 2000–2010

The NO_x emissions from eight types of fossil fuels are presented in Fig. 4. Coal is the most important energy source in China, accounting for about 70% of the total energy consumption (DESNBS, 2000–2010). The combustion of coal produces abundant NO_x, and becomes the biggest contributor for NO_x emissions among all the fossil fuels. Coal consumption increased from 1245.37 Mt (SCE) in 2000 to 3122.36 Mt (SCE) in 2010 (NBS, 2000–2012). Meanwhile, NO_x emissions from coal combustion almost doubled from 7.32 Mt in 2000 to 14.29 Mt in 2010, accounting for about 60% of the national total. With increased use of other types of fossil fuels, the share of NO_x emissions from coal combustion slightly decreased from 62.0% in 2000 to 58.7% in 2010. Diesel was the second largest contributor for NO_x emissions, followed by coke, crude oil, gasoline, residual oil, kerosene, and natural gas. NO_x emissions from diesel and gasoline cars increased rapidly with the significant increase in the number of vehicles in China. From 2000 to 2010, NO_x emissions from diesel and gasoline engines increased from 1.42 Mt and 0.69 Mt to 4.18 Mt and 1.39 Mt, respectively. The share of diesel engines as part of the national total for NO_x rose from 12.0% to 17.2%, while the share of gasoline engines impact on NO_x emissions declined slightly from 5.8% to 5.7% with effective control measures, such as the use of the three-way catalyst. Hence, the treatment of NO_x from diesel engines has recently become a big challenge in China.

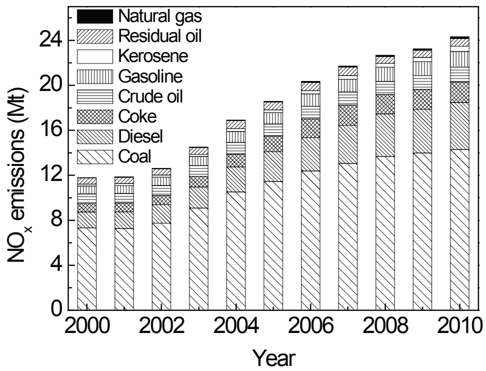

Fig. 4 NO_x emission inventory of fossil fuels in China

3.4 NO_x emission inventory and the intensity of provinces, 2000–2010

This study covered 31 administrative regions across mainland China. Hong Kong, Macao, and Taiwan were not included since detailed information from these areas was not available. Fig. 5a shows the NO_x emission trends in different provinces in 2000, 2005, and 2010. All the provincial NO_x emissions represent a growth trend. Due to the implementation of China's Western Development Strategy since 2000, more factories and fossil-fuel power plants have been developed in the western provinces. Accordingly, the increase of NO_x emissions in some western provinces was higher than that in the eastern provinces. NO_x emissions in Inner Mongolia, Ningxia, and Shaanxi increased by 4.18, 3.15, and 2.78 times, respectively, while the national NO_x emissions increased by 2.06 times from 2000 to 2010. Shandong, Hebei, Guangdong, Jiangsu, and Henan provinces were the five largest contributors to NO_x emissions among all the 31 provinces. The NO_x emissions for these five provinces were calculated as 2.09 Mt, 1.68 Mt, 1.59 Mt, 1.58 Mt, and 1.34 Mt in 2010, respectively, while Tibet only emitted about 0.03 Mt. In 2010, the five provinces that accounted for 38.9% of the national total GDP contributed to 34.0% of the national total NO_x emissions while only occupying 8.2% of the total area. The unbalanced economic development is the primary cause of the unbalanced NO_x emissions.

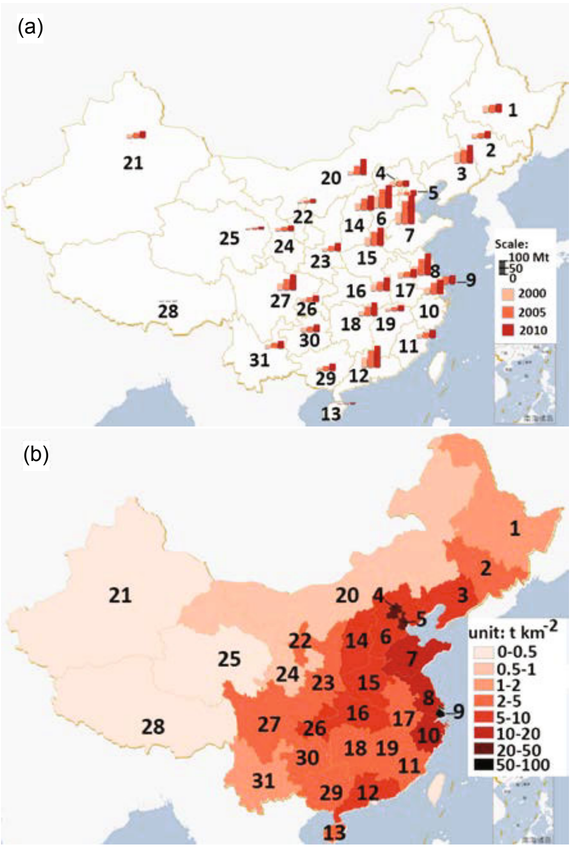

Fig. 5 NO_x emission trends (a) and distributions (b) of different provinces in China

Eastern China: 1. Heilongjiang, 2. Jilin, 3. Liaoning, 4. Beijing, 5. Tianjin, 6. Hebei, 7. Shandong, 8. Jiangsu, 9. Shanghai, 10. Zhejiang, 11. Fujian, 12. Guangdong, 13. Hainan. Central China: 14. Shanxi, 15. Henan, 16. Hubei, 17. Anhui, 18. Hunan, 19. Jiangxi. Western China: 20. Inner Mongolia, 21. Xinjiang, 22. Ningxia, 23. Shaanxi, 24. Gansu, 25. Qinghai, 26. Chongqing, 27. Sichuan, 28. Tibet, 29. Guangxi, 30. Guizhou, 31. Yunnan

In 2010, the three lowest ratios of NO_x emissions to gross regional product (GRP) in China were 3.03×10^{-4} kg/CNY for Beijing, 3.45×10^{-4} kg/CNY for Guangdong, and 3.70×10^{-4} kg/CNY for Shanghai, respectively. In the meantime, the three highest ratios were 17.20×10^{-4} kg/CNY for Ningxia, 13.26×10^{-4} kg/CNY for Qinghai and 11.69×10^{-4} kg/CNY for Guizhou, respectively. It can be seen that NO_x emissions per unit of GRP in developed provinces, for instance Beijing, Shanghai and Guangzhou, is much lower than those in less developed provinces. The emission gap is mainly caused by different compositions of GRP. Taking Beijing's GRP as an example, the tertiary industries contributed about 75.1%, while the primary and secondary industries account for 0.9% and 24.0%, respectively. In contrast, the tertiary industries only accounted for 41.6% of the GRP in Ningxia while 9.4% and 49.0% came from the primary and secondary industries (NBS, 2000–2012). It is well known that the tertiary industries produces less pollutants and are more environmentally-friendly. Hence, a higher proportion of tertiary industries in the industrial structure poses a positive effect on NO_x emission control.

Fig. 5b shows the NO_x emission intensity of each province in 2010. The regions with the most intensive NO_x emission were located in the eastern China provinces that are more developed, such as Shanghai (100.00 t/(km^2·y)), Tianjin (35.06 t/(km^2·y)), Beijing (25.42 t/(km^2·y)), Jiangsu (15.41 t/(km^2·y)), Shandong (13.57 t/(km^2·y)), and Zhejiang (10.13 t/(km^2·y)). On the other hand, the western provinces are sparsely populated, less developed, and with relatively large undeveloped areas. The NO_x emission intensity of these provinces was far less than that of the eastern provinces, for instance, Xinjiang (0.30 t/(km^2·y)), Qinghai (0.25 t/(km^2·y)), and Tibet (0.03 t/(km^2·y)). High NO_x emission intensity resulted in poor air quality since NO_x is one of the main causes of haze. Many big cities in central and eastern China have frequently suffered from haze in winter. Consequently, health issues resulting from haze have aroused wide spread public attention in recent years. The hazardous dense haze, covering most parts of central and eastern China in January 2013, has enveloped a total of 1.4 million square kilometers of China (MEP, 2013). These regions are those with high NO_x emission intensity, such as Beijing, Tianjin, Hebei, Henan, Shandong, Jiangsu, etc. This illustrates that haze is closely related to the severe intensities of NO_x emissions. To improve ambient air quality in China, NO_x emission reduction is drastically needed. In consideration of the widespread pollution sources, it is best to have joint control of NO_x emissions by all the provinces.

3.5 NO_x emission inventory of economic sectors, 2000–2010

NO_x emissions from all the main economic sectors have been increasing for the past ten years. Manufacturing, electricity, and transportation were the three largest contributors, which together compromised about 90% of the national NO_x emissions as shown in Fig. 6. Manufacturing that was the largest NO_x emission source, emitted 8.34 Mt NO_x in 2010, which was 1.9 times than that in 2000. The rapid and sustainable development of the national economy has resulted in an increasing demand for power during the past decade. Moreover, it is reported that thermal power consumption accounted for 80% of the national total electricity production (NBS, 2000–2012). Hence, the electricity sector that was the second largest contributor for NO_x emissions emitted 7.85 Mt NO_x in 2010, which was 2.0 times the total NO_x emissions in 2000, as shown in Table 3.

Fig. 7 shows the NO_x emissions for the transportation sector, which increased by 2.7 times from 2000 to 2010, due to the rapid increase of vehicles in China. The number of vehicles increased from 16.1 million in 2000 to 78.0 million in 2010 (NBS, 2000–2012). Consequently, fuel consumption has increased significantly in this ten-year-period, which resulted in the dramatic increase of NO_x emissions. NO_x emissions from the transportation sector were 5.80 Mt in 2010, which made up of about 23.8% of the national total.

To control NO_x emissions, China has promulgated a series of emission standards for thermal power plants as illustrated in Table 4. With the implementation of improved emission standards in 2004, NO_x emissions from the electricity sector decreased by 2.5% during the period 2005–2010 as shown in Fig. 6.

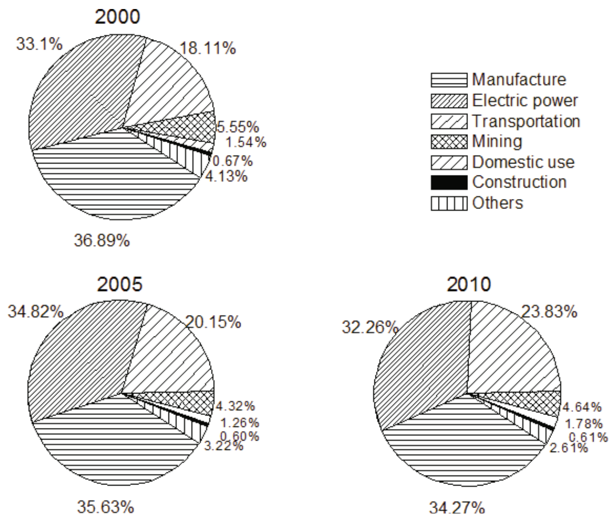

Fig. 6 Economic sector shares on NO_x emissions in 2000, 2005, and 2010

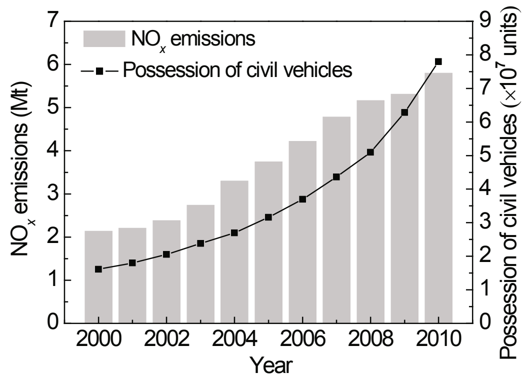

Fig. 7 Transportation NO_x emissions and possession of civilian vehicles in China

Table 3 NO_x emission inventory by economic sectors (unit: Mt)

Year	NO_x emissions							
	Manufacture	Electricity	Transportation	Mining	Domestic use	Construction	Others	Total
2000	4.36	3.91	2.14	0.65	0.18	0.08	0.49	11.81
2001	4.26	3.97	2.21	0.66	0.18	0.08	0.50	11.86
2002	4.40	4.38	2.39	0.67	0.19	0.09	0.51	12.62
2003	5.01	5.09	2.74	0.87	0.20	0.09	0.51	14.53
2004	6.03	6.00	3.30	0.68	0.22	0.10	0.59	16.92
2005	6.62	6.47	3.74	0.80	0.23	0.11	0.60	18.59
2006	7.18	7.14	4.22	0.83	0.24	0.12	0.62	20.35
2007	7.47	7.57	4.79	0.91	0.25	0.12	0.62	21.72
2008	7.92	7.57	5.17	0.98	0.36	0.12	0.58	22.69
2009	8.03	7.77	5.31	1.04	0.39	0.13	0.59	23.26
2010	8.34	7.85	5.80	1.13	0.43	0.15	0.63	24.33

Table 4 Emission standard for air pollutions from thermal power plants in China

Emission standard	Implementation time of new plant	NO_x (mg NO_2/m^3)		
		Coal-fired boiler	Oil-fired boiler	Gas-fired boiler
GB 13223–1996	1997	650		
GB 13223–2003	2004	650	200	80
GB 13223–2011	2012	100	100	50

It can be predicted that the electricity sector's share on total NO_x emissions will decrease sharply when the emission standard for air pollutions from thermal power plants in China (GB 13223–2011) is implemented, as the NO_x emission limitation of a coal-fired boiler is 100 mg NO_2/m^3 in GB 13223–2011, less than 1/6 of that in GB 13223–2003.

Although China has improved its vehicle emission standards for the past decade, the transportation share of NO_x emissions increased from 18.1% in 2000 to 23.8% in 2010. This is due to the remarkable increase of vehicles in China. The number of civilian vehicles exceeded 100 million units in 2012. This indicates that diesel and gasoline consumption will be on the rise with the increase in the number of vehicles. We can predict that the transportation share of NO_x emissions will continue to increase. The rapid increase of vehicle numbers has aroused the Chinese government's attention. It is believed that the growth rate of transportation NO_x emissions will slow down with the implementation of more stricter vehicle emission standards (Euro V, even Euro VI in the future) and automobile purchase restrictions in big cities in China (such as Beijing, Tianjin, and Shanghai).

As the manufacturing industry is made up of many different production sectors, its waste gas has the following characteristics: widely distributed emission sources, small-scale, complex chemical components, and various physical conditions. Therefore, it is harder to control NO_x emissions from manufacturing than from electricity and transportation. Existing reduction technologies such as selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) cannot treat manufacturing waste gas effectively. Manufacturing's share of NO_x emissions is expected to increase in the future if NO_x emissions from the electricity and transportation sectors are kept under control. Hence, new control techniques need to be developed to treat NO_x emissions from the manufacturing sector.

3.6 Prediction of future NO_x emissions

We designed three different scenarios to analyze the NO_x emission trends in China for the period 2011–2020, including a relaxed control scenario, a reference control scenario, and a strict control scenario. The relaxed control scenario assumes that the energy structure and NO_x control levels are the same as that in 2010, which means the energy consumption and NO_x emissions per unit of GDP will not change between 2011 and 2020 (t=0, d=0, where t is the average annual decline rate of energy consumption per unit of GDP and d is the average annual decline rate of NO_x emissions per unit of GDP). The reference scenario assumes that the progress of reduction technology innovation and energy structure adjustment are the same as that during the period 2005–2010. As a result, the average annual decline rates of energy consumption and NO_x emissions per unit of GDP have the same values as those during the period 2005–2010 (t=0.042, d=0.052), respectively. The strict control scenario assumes Chinese government will implement NO_x control strategies strictly as described in the 12th FYP (t=0.048, d=0.085). The Chinese government will promulgate a series of strict emission standards and promote the application of NO_x reduction technology, including a low NO_x burner (LNB), over fire air (OFA), SCR, and SNCR. For example, all the thermal power plants will need to be equipped with SCR to meet the new NO_x emission standards of 2011.

The average annual growth rate of GDP for all the three scenarios was derived from the Report to the Eighteenth National Congress of the Communist Party of China and 12th FYP (g=0.07–0.075). The values of the other parameters were based on each scenario under different control levels.

The predicted results are summarized in Fig. 8 and Fig. 9, which were calculated using Eqs. (2-5) and (2-6). Energy consumption calculated as SCE for all scenarios will continue to increase to meet the demand for economic growth, reaching 6392.0 Mt

(SCE), 4161.9 Mt (SCE), and 3908.5 Mt (SCE) by 2020, respectively. The great demand for energy has caused energy shortages in China. Without further actions on energy conservation policies, like the relaxed control scenario, energy consumption will double during the period 2010–2020, which could aggravate the energy crisis. Consequently, China should strengthen supervision on energy-intensive industries, improve energy efficiency, and promote the utilization of renewable energy.

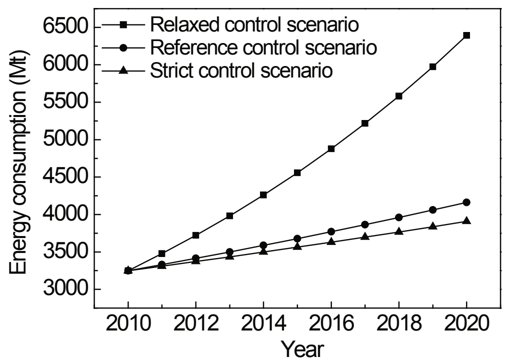

Fig. 8 Prediction of energy consumption (calculated as SCE) in China, 2011–2020

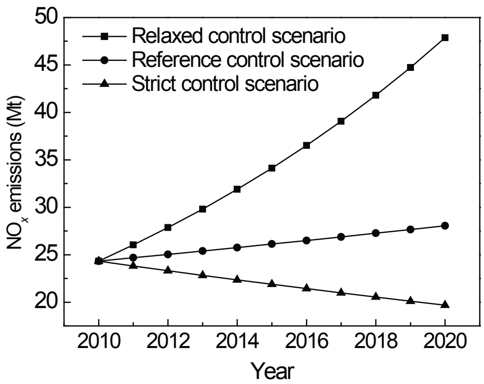

Fig. 9 Prediction of NO_x emissions in China, 2011–2020

Under the relaxed control scenario and reference control scenario, NO_x emissions are expected to raise to 47.9 Mt and 28.1 Mt by 2020, respectively. In theory, under a strict control scenario, NO_x emissions would drop to 21.9 Mt by 2015, about 90% of NO_x emissions in 2010, and 19.7 Mt by 2020. This indicates that China should take strict measures on NO_x emission control to achieve the reduction target of a 10% cut as included in the 12th FYP. In this case, the removal efficiency of national NO_x should reach 61.5% by 2015. However, early policies were unsuccessful at reducing NO_x emissions. In fact, the NO_x emissions in 2011 increased by 5.73% compared with that in 2010 as reported by MEP (2012). The emission factors of cement (Lei *et al.*, 2011) and heavy-duty vehicles (Wu *et al.*, 2012) even increased over the past decade. Hence, to achieve the NO_x reduction target of the 12th FYP, the Chinese government is facing a big challenge on reducing NO_x emissions over the next years. It is quite necessary to combine the following strategies: improvement of the reduction technology, transformation of the economic growth pattern, and strict administrative intervention.

4 Conclusions

This work aims to investigate the emission status of NO_x during the period 2000–2010 and predict the future trends for the period 2011–2020 in China. Although NO_x emissions per unit of GDP decreased by 24.7% during the period 2000–2010, China's NO_x emissions increased by 2.1 times and reached 24.33 Mt in 2010. The growth of NO_x emissions is changing the composition of acid rain in China. Among the national total NO_x emissions, about 60% came from coal consumption, so reducing coal consumption in fire power plants and industrial boilers will provide remarkable mitigations of NO_x emissions. As diesel and gasoline consumption increased year by year, its NO_x emission reductions should not be ignored. NO_x emissions in the eastern provinces are much higher than that in the western provinces. The unbalanced NO_x emissions resulted from the unbalanced economic development in the two regions. When it comes to economic sectors, manufacturing was the biggest contributor for NO_x emissions, followed by electricity and transportation. With the implementation of new emission standards for air pollution from thermal power plants in China since 2013, the electricity share of NO_x emissions will decrease, resulting in the sharp increase in the manufacturing and transportation shares. Hence, in consideration of the complex types of manufacturing NO_x emissions, the Chinese government should focus on the treatment of manufacturing waste gas in the future. In order to achieve a 10% cut in NO_x emissions in the 12th FYP (2011–2015) of China, it is necessary to take strict control measures to reduce NO_x emissions. If so, the removal efficiency of national NO_x should reach 61.5% in 2015.

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中文概要：

本文题目：2000–2020 年中国氮氧化物排放清单及排放趋势
Emission inventory and trends of NO_x for China, 2000–2020

研究目的：建立 2000–2020 年中国氮氧化物排放清单，了解中国主要行业和省份氮氧化物的排放情况，为评估氮氧化物的环境影响和制定相关减排政策提供依据。

创新要点：分析了中国主要省份产业结构对氮氧化物排放量的影响；根据不同情景分析，预测 2020 年中国氮氧化物的排放量。

研究方法：1. 基于自底向上法，根据不同类型化石燃料的氮氧化物排放因子，结合化石燃料消耗量，建立中国 2000–2010 年氮氧化物排放清单；2. 基于 IPAT 方程，并以中国 2000–2010 年的国内生产总值增长数据和氮氧化物排放量为依据，分三种情景，分析 2011–2020 年中国能源消耗和氮氧化物排放趋势。

重要结论：2010 年中国氮氧化物的排放量约是 2000 年的两倍；自 2009 年起，中国氮氧化物总排放量超过了二氧化硫总排放量；主要由于产业结构和地区生产总值的不同，中国东部和西部氮氧化物排放量有明显差异；制造业、电力行业和交通运输业是中国氮氧化物的主要排放源，其中交通运输业氮氧化物排放量呈现逐年增长趋势；预计 2020 年中国氮氧化物排放量为 19.7 Mt。