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Multiscale input–output subsystem model of methane and nitrous oxide emissions from the service sector: a case study of Beijing, China

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ABSTRACT: Urban economies rely on the factors of production (labor, capital, raw materials) and commodities (or services) provided from domestic and foreign markets. This causes environmental pollution in domestic and foreign areas generated by demand that results from urban development. Input–output analyses have been widely used to estimate urban environmental pollution. However, most previous studies adopted a single-region approach, which assumed that the same production technology was used in local, domestic, and foreign urban production systems. Here we constructed a 3-scale input–output model that assumed different production technologies for these 3 types of production systems to more accurately estimate urban environmental pollution. Due to the service-dominated economy of Beijing, a 3-scale input–output subsystem model was constructed and applied to estimate the greenhouse gas (GHG) emissions from the 3 production systems caused by local service development in Beijing. Specifically, we investigated methane (CH_4) and nitrous oxide (N_2O) emissions associated with 3 sources (local production and domestic and foreign imports), 4 components (external, induced, internal, and demand-level components), and 5 demand categories (household consumption, government consumption, investment, domestic exports, foreign exports) of the service sector in Beijing in 2010. Total CH_4 and N_2O emissions from the service sector were estimated to be 5641.25×10^3 and 674.05×10^3 t CO_2-equivalent, accounting for 15.20 and 13.39% of the total CH_4 and N_2O emissions from Beijing, respectively. Local production played a major role in emissions, followed by domestic and foreign imports. Our model can isolate the effects of individual sectors on GHG emissions at different scales, helping urban policymakers formulate specific emission-reduction regulations according to different goals.

KEY WORDS: Input–output model · Greenhouse gas · Urban climate · Service development · Developing economy

1. INTRODUCTION

Climate change has become a worldwide problem with widespread impacts on human and natural systems due to continually increasing anthropogenic greenhouse gas (GHG) emissions (IPCC 2014a). Although long-term warming is mainly driven by carbon dioxide (CO_2) emissions, methane (CH_4) and nitrous oxide (N_2O) (which have relative 100 yr global warming potentials (GWP_{100}) that are 28 and 265 times that of CO_2, respectively) should also be addressed (IPCC 2014b). Reducing emissions of CH_4 and N_2O can be an important element of government mitigation strategies (IPCC 2014a).

Currently, China is the world's largest emitter of GHGs and is therefore under considerable pressure to control its emissions (Wang et al. 2012, Ge & Lei 2014). Cities are considered to play important roles in GHG emissions. Globally, cities contribute to more than two-thirds of the world's energy consumption

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and >70% of global CO_2 emissions (C40 Cities Climate Leadership Group 2011, Lazarus et al. 2013, Ge & Lei 2014). Similarly, in China, the 35 largest cities contained approximately 18% of the country's population and contributed to 40% of the country's CO_2 emissions in 2006 (Dhakal 2009). Metropolitan areas are specifically associated with higher GHG emissions per capita than are smaller cities or rural areas due to differences in production and consumption patterns (Chavez-Baeza & Sheinbaum-Pardo 2014). Beijing, the capital of China, is one of the metropolises in China that has experienced rapid transformation, population growth, construction, and increasing automobile traffic (Feng et al. 2013). With rapid economic and social development, carbon emissions have increased in previous decades in Beijing. Although energy-related CO_2 emissions from Beijing only accounted for 2.52% of the national total in 2006 (Dhakal 2009), the per capita CO_2 emission reached 6.91 t, which was 1.3 times the national average in 2009 (Feng et al. 2013). Moreover, the per capita GHG emission of Beijing was 10.1 CO_2-equivalent (CO_2-eq) that was larger than the per capita GHG emission of Paris (5.2), London (9.6), Sao Paulo (1.4) while smaller than that of New York (10.5), Toronto (11.6) and Sydney (25.8) in 2005 (World Bank 2010). Therefore, to achieve China's CO_2 emission reduction target proposed in 2015, which promised that China would cut its CO_2 emissions by 60 to 65% per unit of gross domestic product (GDP) by 2030 compared to its level in 2005, Beijing should focus on reducing emissions by a similar amount to reductions in other cities in China.

In addition to the dominant role of CO_2 in China's GHG emissions, non-CO_2 GHGs also contributed to 20% of total GHG emissions in 2005 (Department of Climate Change of National Development and Reform Commission of China 2014). In terms of the GWP_{100}, CH_4 and N_2O specifically accounted for 14.30% of the total GHG emissions caused by the Chinese economy in 2007 (Chen & Zhang 2010). Especially in metropolises, larger waste disposal due to dense populations, and rapid growth of vehicles, can lead to more abrupt increases in CH_4 and N_2O emissions compared to those in small cities. With the expansion of the urban population and increased private car ownership in Beijing, municipal waste disposal contributed 45.48% of total CH_4 emissions, and fossil fuel combustion (e.g. gasoline combustion) caused 41.91% of total N_2O emissions in 2007 (Guo et al. 2012a). Some studies have focused on CO_2 emissions in Beijing (Schleicher et al. 2011, 2013, Feng & Zhang 2012, Guo et al. 2012b, Chen et al. 2013, Tian et al. 2013, Zhang et al. 2013, Ge & Lei 2014, Mi et al. 2015), but few have examined CH_4 and N_2O emissions. Guo et al. (2012a) indicated that total embodied CH_4 and N_2O emissions in Beijing in 2007 were 246×10^4 and 881×10^3 t CO_2-eq, respectively. Zhou et al. (2010) also calculated the total embodied CH_4 and N_2O emissions in Beijing in 2002 and obtained larger CH_4 emissions of 7092×10^3, and ~834×10^3 t of N_2O emissions. Their estimations can be used to compare emissions between sectors and assess direct and indirect emissions from a single sector. However, their estimations could be more accurate because they assumed that imported commodities had the same embodied emission intensities as local commodities in Beijing. A more realistic assumption can be adopted based on different production technologies and energy structures in Beijing, China, and foreign countries. Moreover, the economy in Beijing has transformed from a manufacture-dominated to a service-dominated structure, indicating that the quantity and structure of GHG emissions resulting from service development should be given more attention. Our study intends to improve the estimation method and investigate the quantity, structure, and paths of CH_4 and N_2O emissions generated from service development in Beijing. Moreover, in practice, policymakers have not paid enough attention to non-CO_2 emissions and have not included CH_4, N_2O, and other GHGs in the frameworks of pollution control policies.

Between 2006 and 2010, Beijing achieved its goals for energy savings and emissions reduction established by the 11th Five-Year Plan (Wang et al. 2012). During this period, the government began forcing certain industrial sectors, such as chemical and nonferrous metal producers, to control their pollution emissions. By contrast, the service sector is expected to remain more stable and is predicted to account for more than 79% of the regional GDP by 2020, according to Beijing's 13th Five-Year Plan. The service sector is defined in Table 1 according to China's National Industrial Classification (GB/T 4754-2011). The service sector, including distributive services (transportation, communication, commerce), producer services (financial and professional), social services (health, education, defense), and personal services (domestic, hotels, restaurants, leisure), is considered to produce intangible goods and require relatively less natural capital and more human capital than agricultural or industrial production (Browning & Singelmann 1975, Piaggio et al. 2015). This leads to its perception as environmentally friendly, with relatively clean production activities (excluding transport-related sectors) (Gallouj & Djellal 2010,

Table 1. Service sector classification. Sources: China's National Industrial Classification (GB/T 4754-2011); input–output extension table for Beijing in 2010 (BMBS 2012)

Service sector classification	Short sector name
Transportation, storage, posts and telecommunications	Transportation
Information transmission, computer services, and software	Information services
Wholesale trade and retail trade	Wholesale and retail
Hotel and restaurants	Hotel and restaurants
Finance	Finance
Real estate trade	Real estate
Tenancy and commercial services	Commercial services
Scientific studies and technical services	Scientific services
Water, environment, and municipal engineering conservancy	Municipal services
Resident services and other services	Resident services
Education	Education
Health care, social security, and social welfare	Social welfare
Culture, art, sports, and recreation	Culture and sports
Public management and social organization	Public management

Piaggio et al. 2015). However, regarding carbon emissions in Beijing in 2010, Ge & Lei (2014) indicated that although direct emissions due to the service sector accounted for 32.47% of Beijing's total emissions, the service sector emitted 50.89% of Beijing's total emissions if indirect emissions were also considered. Furthermore, Zhang et al. (2014) noted that Beijing is transitioning from a manufacturing-dominated economy to a service-dominated economy, and thus the energy consumption embodied by the service sector accounted for nearly half of the total GHG emissions from all sectors in Beijing in 2007. Therefore, due to the service-dominant economy of Beijing, other GHG emissions should also be estimated and compared with CO_2 emissions to help the government create a more systematic and integrated GHG mitigation policy framework.

Input–output analyses are based on well-established methodology and have been widely used in GHG investigations (Lenzen 1998, Munksgaard & Pedersen 2001, Lenzen et al. 2004, Mäenpää & Siikavirta 2007, Wiedmann et al. 2007, Wiedmann 2009, Hristu-Varsakelis et al. 2010, Chen & Chen 2011, Cortés-Borda et al. 2014, Akpan et al. 2015, Zhang et al. 2015). Input–output analysis can be used to identify emissions associated with production in each sector and to identify the impacts of changes in the final demands of different sectors on total or sectoral emissions (Alcántara & Padilla 2009). The purpose of this paper is to construct a multiscale input–output subsystem model and investigate the direct and indirect CH_4 and N_2O emissions generated by the service sector of Beijing's economy from 3 new perspectives. (1) The most recently released input–output extension table for Beijing (2010) was used to comprehensively evaluate CH_4 and N_2O emissions based on the final demand of the service sector. (2) Compared to the single-region assumption used in many urban input–output studies, a 3-scale input–output model of Beijing was constructed to obtain information regarding CH_4 and N_2O emissions generated by local, domestic, and foreign demands for services. (3) A subsystem was introduced to isolate the quantities, structures, and paths of CH_4 and N_2O emissions for individual sectors.

2. DATA AND METHODS

2.1. Model specification

The input–output subsystem model provides a useful framework that gives specific information regarding the effects generated from individual units (Butnar & Llop 2011). This analysis decomposes CH_4 and N_2O emissions from the service sector into 4 components, namely an external component, an induced component, an internal component, and a demand-level component.

Input–output subsystem models have been used in environmental analyses of specific regions, such as in studies by Alcántara & Padilla (2009), Llop & Tol (2013), and Ge & Lei (2014). These studies made the implicit assumption that the intensity of environmental pollutant emissions was the same for imported goods and locally produced goods. However, a more realistic assumption is that different emission intensities exist for imported goods and locally produced goods because different areas have specific production technologies and energy structures.

To investigate CH_4 and N_2O emissions from Beijing's services, we first constructed a 3-scale supply-and-demand system, as shown in Fig. 1. For the inflow, the local production process of services in Beijing can be modeled using intermediate inputs from Beijing, other regions in China, and foreign countries. For the outflow, the output of services from Beijing can be sold in Beijing, other regions of China, and foreign countries. Along with the inflow and outflow, CH_4 and N_2O emissions occur in local, domestic, and foreign areas. For example, the production

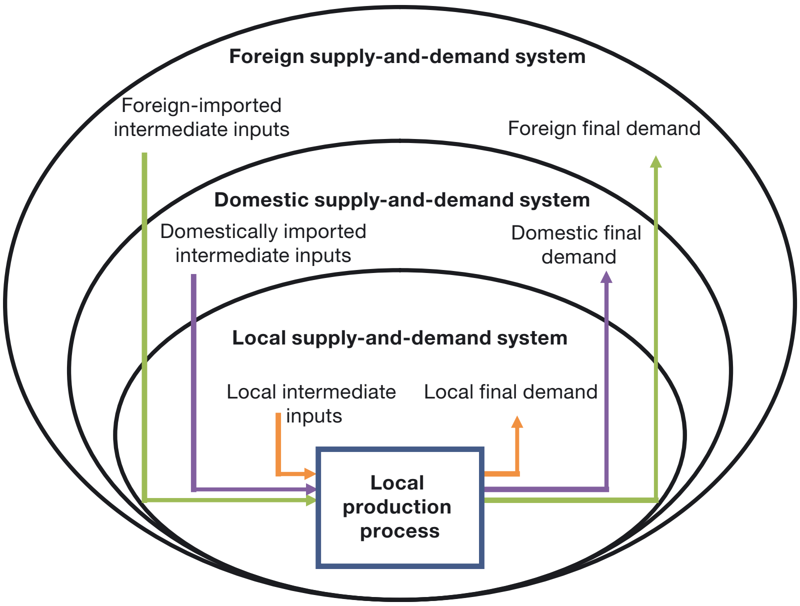

Fig. 1. Three-scale supply-and-demand system for urban commodities and services in the Beijing economy

process of services in Beijing requires electricity produced in Shanxi province, China. Power plants in Shanxi province utilize coal to produce electricity and meet the demands of Beijing services. Therefore, Shanxi province experiences the CH_4 and N_2O emissions caused by Beijing services. Due to the diverse energy structures and production technologies, CH_4 and N_2O emission factors for the electricity sector vary between Beijing and Shanxi. Thus, a 3-scale supply-and-demand system should be constructed.

Moreover, we divide the local, domestic, and foreign supply-and-demand systems into a services subsystem (category *S*) and non-services subsystem (category *M*). The total emissions of CH_4 and N_2O due to services development in Beijing can be determined using the 3-scale model, as shown in Fig. 2. Total CH_4 and N_2O emissions from Beijing services include emissions embodied in production processes and in the consumption processes of outputs. Additionally, the CH_4 and N_2O emissions associated with production processes can be divided into an external component, an induced component, and an internal component. The external component is the emissions from subsystem *M* due to the demand for *S*. The induced component is the emissions from subsystem *S* due to the demand for *M*. The internal component is the emissions from subsystem *S* due to the demand for *S*. The CH_4 and N_2O emissions associated with the consumption process are defined as the demand-level component, which is the emissions due to the demand for *S*. Therefore, the total CH_4 and N_2O emissions due to the demand for services comprise these 4 components.

To integrate the 3-scale commodities or service flows and CH_4 and N_2O flows within and across the boundaries of the Beijing economy, a 3-scale input–output table was compiled (Table 2). At each scale, total emissions consisted of the external component, the induced component, the internal component, and the demand-level components. The detailed formulations are described in Supplement 1 at www.int-res.com/articles/suppl/c069p247_supp.pdf.

2.2. Data

At the local scale, the CH_4 and N_2O emission factors of 8 types of energy fuels were calculated based on the 2006 Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories. Data regarding local energy consumption were obtained from the Beijing Statistical Yearbook 2011 (BMBS 2011). The emission factors are shown in Table 3. The input–output data for Beijing used in this study are from the input–output extension table of Beijing from 2010 (BMBS 2012). This is the latest input–output table for Beijing. Because the input–output table for Beijing is published every 5 yr, to enhance the temporal aspect of the data, the department of statistics constructs input–output extension tables for Beijing in the third year of each 5 yr interval based on updated input–output table technology. The level of disaggregation in the input–output extension table is 42 sectors. However, to match the energy sector classification of the Beijing Statistical Yearbook 2011, we combined some sectors from the input–output sector classification in this paper based on current prices. Our study includes 40 sectors, in which sectors 1–26 are non-service sectors and sectors 27–40 are service sectors.

At the local scale, the domestic energy consumption data were obtained from the China Energy Statistical Yearbook 2011 (NBS 2011). Moreover, the emissions also include agriculture activities, fugitive emissions. Fugitive emissions mean the (i.e. emissions from pressurized equipment due to leaks and other unintended or irregular releases of gases — fugitive emissions mainly source from coal mining in China) waste associated with CH_4, and agriculture

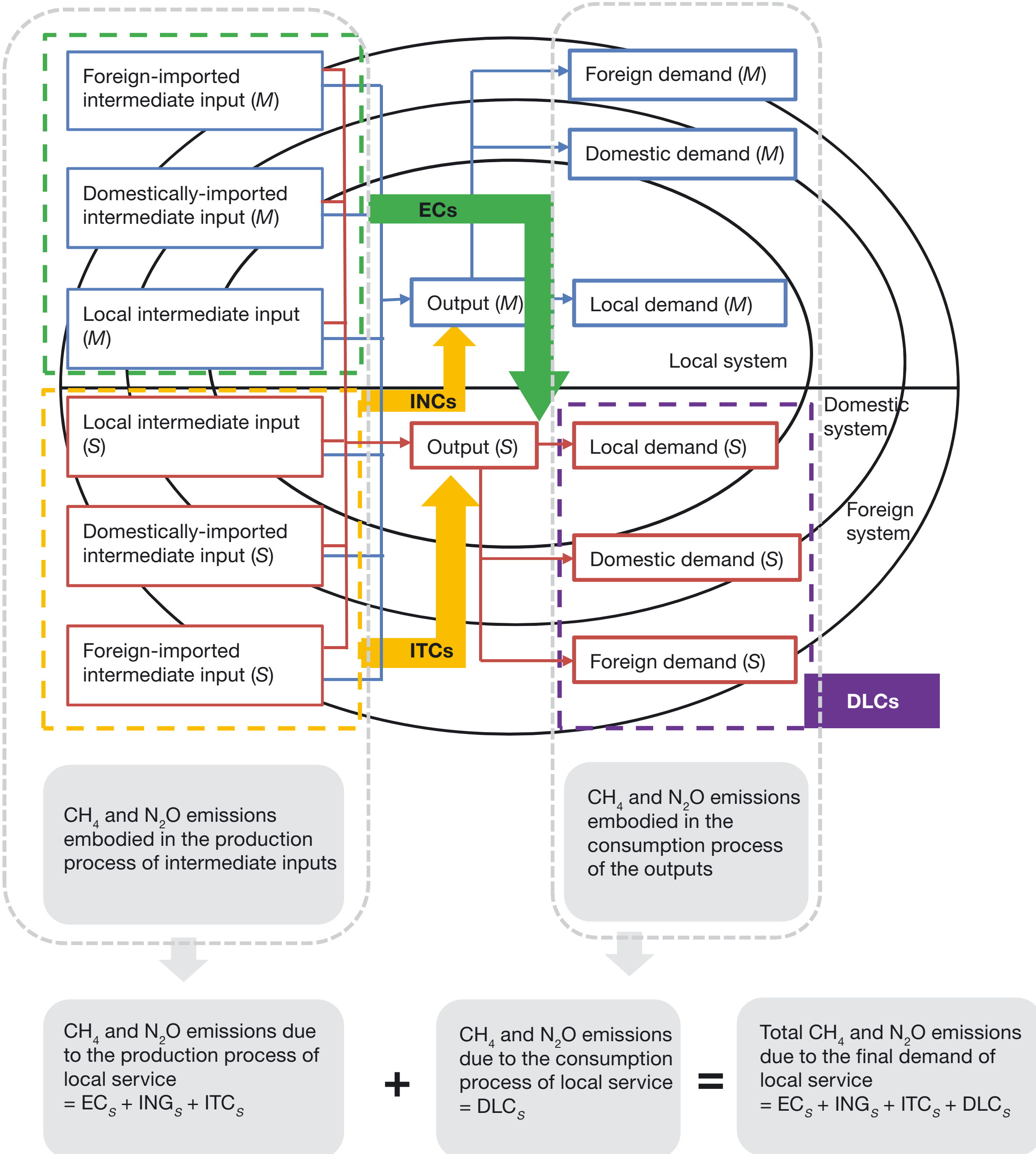

Fig. 2. Three-scale diagram of CH_4 and N_2O emissions due to the demand for services. EC: external component, INC: induced component, ITC: internal component, DLC: demand-level component. Category S: services subsystem, category M: non-services subsystem. Gray dashed boxes — left and right: emissions from the production and consumption processes, respectively. Colored dashed boxes — green: non-service intermediate input for non-service and service sector production; yellow: service intermediate input for non-service and service sector production; purple: output of service sectors for consumption. Shaded boxes within gray dashed boxes summarize the information in those boxes. Shaded boxes at the bottom show relationships among emissions from the production and consumption processes and total emissions. Thin solid colored arrows: flows of commodities or services. Thick solid colored arrows: emissions from different production components — green (ECs): emissions from the non-service production process due to local service demand; yellow (INCs): emissions from the service production process due to the local non-service demand; yellow (ITCs): emissions from the service production process due to the local service demand. Purple solid box: emissions from the local service consumption process in local, domestic and foreign scales. Concentric ellipses: 3 scales of commodities or service trading (local, domestic and foreign systems in the innermost, middle and outermost ellipses). Black horizontal line separates these 3 scales into service (upper) and non-service (lower) sectors

Table 2. Three-scale input–output table for the Beijing economy. z_{ij}^L, z_{ij}^D, and z_{ij}^F represent the local, domestically imported, and foreign-imported intermediate inputs from sector *i* to sector *j*, respectively; y_j^{LL}, y_j^{LD}, and y_j^{LF} represent the local final use, domestic exports, and foreign exports of local sector *j*'s commodity or service produced by the local intermediate inputs, respectively; y_j^{DL}, y_j^{DD}, and y_j^{DF} indicate the local final use, domestic exports, and foreign exports of local sector *j*'s commodity or service produced by the domestically imported intermediate inputs, respectively; and y_j^{FL}, y_j^{FD}, and y_j^{FF} represent the local final use, domestic exports, and foreign exports of local sector *j*'s commodity or service produced by the foreign-imported intermediate inputs, respectively

	Intermediate use			Local	Domestic	Foreign
	Sector 1	…	Sector n	final use	export	export
Local intermediate inputs						
Sector 1	z_{11}^L	…	z_{1n}^L	y_1^{LL}	y_1^{LD}	y_1^{LF}
…	…	…	…	…	…	…
Sector n	z_{n1}^L		z_{nn}^L	y_n^{LL}	y_n^{LD}	y_n^{LF}
Domestically imported intermediate inputs						
Sector 1	z_{11}^D	…	z_{1n}^D	y_1^{DL}	y_1^{DD}	y_1^{DF}
…	…	…	…	…	…	…
Sector n	z_{n1}^D		z_{nn}^D	D^L	y_n^{DD}	y_n^{DF}
Foreign- imported intermediate inputs						
Sector 1	z_{11}^F	…	z_{1n}^F	y_1^{FL}	y_1^{FD}	y_1^{FF}
…	…	…	…	…	…	…
Sector n	z_{n1F}^L		z_{nn}^F	y_n^{FL}	y_n^{FD}	y_n^{FF}

Table 3. CH_4 and N_2O emission factors for various fuel types in China. Values are kg (per kg of fuel), unless otherwise indicated

	N_2O emissions	CH_4 emissions
Coal	3.14×10^{-5}	2.09×10^{-5}
Coke	4.27×10^{-5}	2.85×10^{-5}
Gasoline	2.59×10^{-5}	1.29×10^{-4}
Kerosene	2.59×10^{-5}	1.29×10^{-4}
Diesel oil	2.56×10^{-5}	1.28×10^{-4}
Fuel oil	2.51×10^{-5}	1.26×10^{-4}
Liquefied petroleum gases	5.02×10^{-5}	5.02×10^{-5}
Natural gas (m^3)	3.90×10^{-6}	3.90×10^{-5}

Table 4. Main characteristics of 3-scale sectoral CH_4 and N_2O emission intensities in 2010. Values are tons CO_2-equivalent per 10 000 CNY

	Range	Average
Local emissions		
N_2O	8.30×10^{-6} to 1.90×10^{-1}	5.60×10^{-3}
CH_4	2.55×10^{-6} to 9.21×10^{-1}	1.25×10^{-2}
Domestic emissions		
N_2O	4.86×10^{-7} to 7.95×10^{-1}	3.81×10^{-2}
CH_4	1.06×10^{-5} to 2.65×10^{0}	4.69×10^{-1}
Foreign emissions		
N_2O	7.06×10^{-5} to 9.65×10^{-1}	3.30×10^{-2}
CH_4	7.67×10^{-5} to 1.52×10^{0}	1.95×10^{-1}

activities that use N_2O, which were estimated according to Guo et al. (2012a). The CH_4 and N_2O emissions per unit sectoral output in Beijing are shown in Table 3.

At the domestic scale, environmental accounts data for China from the World Input–Output Database (WIOD) were used to estimate CH_4 and N_2O emissions per unit sectoral output. The major CH_4 and N_2O emission sources include fossil fuel combustion, agriculture activities, fugitive emissions, and waste. However, the newest environmental accounts data were only available for 2009. Due to insufficient data, we assumed that the emission intensity in 2010 was the same as the emission intensity in 2009. The CH_4 and N_2O emissions per unit sectoral output in China were then calculated, as displayed in Table 4.

At the foreign scale, the environmental accounts data for major countries from the WIOD were adopted to estimate the average emission intensities of foreign CH_4 and N_2O emissions. The major countries include 27 EU countries and 13 other countries. Similarly, the newest environmental accounts data for the major countries were only available for 2009. Thus, the assumption that we used at the domestic scale was again adopted. The average CH_4 and N_2O emissions per unit sectoral output in foreign countries were calculated, as displayed in Table 4.

The CH_4 and N_2O emissions per unit sectoral output at the local, domestic, and foreign scales were calculated (Table 4). For N_2O and CH_4, the average sectoral emission intensities in Beijing are 0.0056 and 0.0125 t CO_2-eq per 10 000 Chinese Yuan (CNY — 10 000 CNY was approximately US$1511 in 2010), respectively, which are both smaller than the average levels in China (0.0381 and 0.4692 t CO_2-eq per 10 000 CNY) and in foreign countries (0.0330 and 0.1953 t CO_2-eq per 10 000 CNY). Furthermore, the average levels in foreign countries are lower than the average levels in China. Detailed information regarding sectoral emissions is provided in Supplement 2 at www.int-res.com/articles/suppl/c069p247_supp.pdf.

3. RESULTS

This section reports 4 types of information: the direct and total emissions associated with services, the total emissions generated by the demand for services divided into 4 components, the emissions

Table 5. Main characteristics of direct and total CH_4 and N_2O emissions generated by services in Beijing in 2010. CO_2-eq: CO_2-equivalent

	CH_4		N_2O	
	1000 t CO_2-eq	% total emissions	1000 t CO_2-eq	% total emissions
Direct emissions				
Range	46.80–149.10	1.89–6.01	0.42–37.76	0.05–4.28
Average	67.74	2.73	5.80	0.66
Total	948.40	38.25	81.14	9.21
Total emissions				
Range	30.64–1835.40	0.08–4.94	3.08–125.29	0.06–2.49
Average	402.95	1.09	48.15	0.96
Total	5641.25	15.20	674.05	13.39

generated by the demand for services at the 3 scales, and the emissions generated by the different categories of demand for services.

3.1. Direct and total emissions

Table 5 displays the main characteristics of direct and total CH_4 and N_2O emissions associated with services. To compare these 2 types of GHG emissions in the same dimension, CO_2-eq based on the GWP_{100} values from the IPCC Fifth Assessment Report (IPCC 2014b) were adopted. CH_4 and N_2O have GWP_{100} values that are 28 and 265 times that of CO_2, respectively.

Direct emissions included emissions primarily due to emission sources (e.g. fossil fuel combustion) in the production process of a sector. Total emissions included direct emissions and indirect emissions due to the specific sectoral production associated with other production activities. Direct emissions of CH_4 and N_2O by services were 948.40 and 81.14 × 10^3 t CO_2-eq, respectively, accounting for 38.25 and 9.21% of the total direct CH_4 and N_2O emissions generated by all production activities in Beijing, respectively. However, total (including direct and indirect) emissions of CH_4 and N_2O generated by all production sectors to meet the demand for services accounted for 15.20 and 13.39% of the total emissions of the Beijing economy, respectively, as shown in Table 5. The proportion of total direct CH_4 emissions by services to the total direct emissions was greater than the proportion of total CH_4 emissions (including direct and indirect emissions) by services to total overall emissions. Therefore, indirect CH_4 emissions caused by the pull effect from services to other sectors were not significant. Direct CH_4 emissions generated during the production of services were of major importance; thus, they should receive more attention from policymakers. By contrast, the proportion of direct emissions was smaller than that of total emissions for N_2O emissions from services. For N_2O, the pull effects of the service sectors on emissions were more significant. However, the roles played by the different service sectors were very different for these 2 types of emissions, as shown in Table 5. Detailed information on direct and total emissions generated by services in Beijing in 2010 is given in Supplement 3 at www.int-res.com/articles/suppl/c069p247_supp.pdf.

3.2. Components of CH_4 and N_2O emissions

To examine the CH_4 and N_2O emission paths from the service sector, total emissions were divided into 4 components: an external component (EC), an induced component (INC), an internal component (ITC), and a demand-level component (DLC). Fig. 3 illustrates the results of this division of emissions based on the contributions of the EC, INC, ITC, and DLC to the total emissions of each production service sector.

Fig. 3a shows that the DLC was the most important source of CH_4 emissions, indicating that the service production required to meet the final consumption of services caused the greatest CH_4 emissions.

In 10 service sectors, namely transportation, information services, wholesale and retail, real estate, scientific services, municipal services, resident services, education, culture and sports and public management, the DLC-dominated emissions ranged from 29.41 to 96.49% of each sector-based total. Of these 10 sectors, culture and sports, information services, and municipal services sectors exhibited the largest portions of DLC emissions, accounting for >85% of the sectoral totals.

In the hotel and restaurant sector and the social welfare sector, the EC contributed the most to emissions. In the commercial services sector and the finance sector, the ITC contributed to the largest amount of the sectoral total.

Fig. 3b shows the division of sectoral N_2O emissions between the 4 components. Unlike the sectoral CH_4 emissions, the EC and DLC played the most important roles in sectoral N_2O emissions for most services.

Nine sectors, namely wholesale and retail, hotel and restaurant, finance, real estate, commercial services, scientific services, education, social welfare,

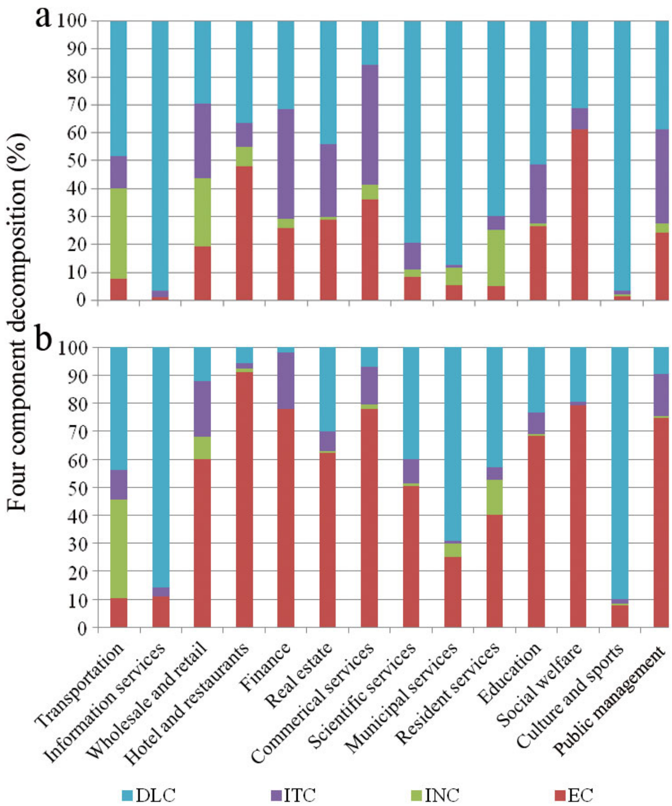

Fig. 3. External component (EC), induced component (INC), internal component (ITC), and demand-level component (DLC) of sectoral (a) CH_4 and (b) N_2O emissions from services in Beijing in 2010

and public management, exhibited significant contributions from the EC to total N_2O emissions. The largest EC contributions to total sectoral emissions were in the hotel and restaurants, social welfare, and the commercial services sectors, accounting for >75 % of the sectoral totals.

The DLC was the most important source of total sectoral emissions in the cultural and sports, information services, municipal services, transportation, and wholesale and retail sectors, accounting for 33.60 to 49.09 % of the sectoral totals.

Fig. 3 shows that in addition to the quantitative differences in CH_4 and N_2O emissions between sectors, there is also a pattern associated with the relative importance of the DLC. For most services, both CH_4 and N_2O emissions were impacted by the final consumptions of these services. Therefore, policymakers should focus more on CH_4 and N_2O emissions when upgrading final consumption structures and promoting service development. Moreover, due to the sectoral variations in CH_4 and N_2O emissions, policies addressing these GHGs should also differ in different sectors.

3.3. Three scales of CH_4 and N_2O emissions

Total CH_4 and N_2O emissions were divided into the local, domestic, and foreign scales, as shown in Fig. 4.

Fig. 4a shows that for most services, including wholesale and retail, hotel and restaurant, finance, real estate, commercial services, resident services, education, and public management, the CH_4 emissions at the local scale dominated the sectoral total, ranging from 73.58 to 99.92 %. The largest contributions of local emissions to the sectoral totals were in real estate, finance and public management sectors, accounting for >97 % of the sectoral totals. In addition, emissions due to domestic imports dominated 4 services (information services, municipal services, social welfare and culture and sports sectors). Finally, emissions caused by foreign imports displayed the

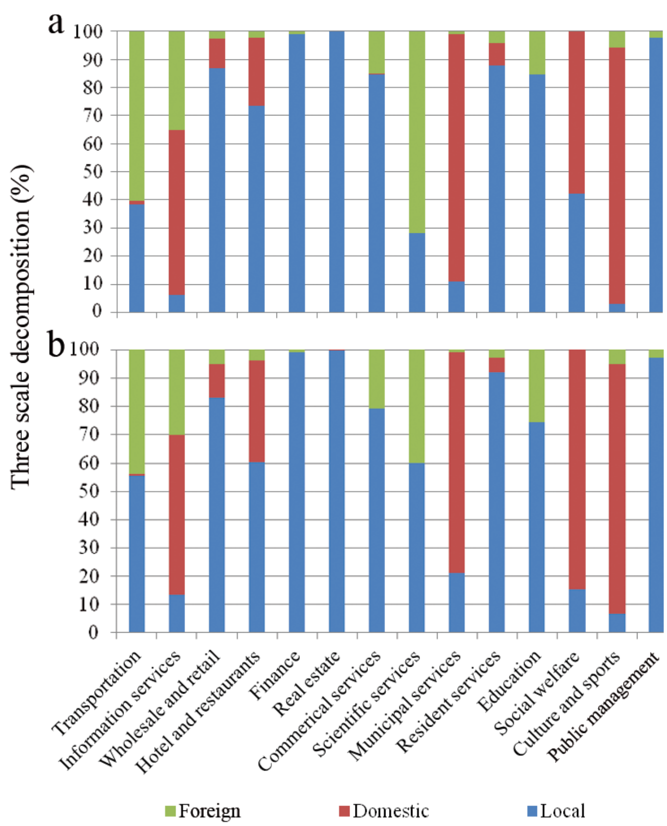

Fig. 4. Local, domestic, and foreign scales of sectoral (a) CH_4 and (b) N_2O emissions associated with services in Beijing in 2010

largest contribution to the sectoral total in the transportation sector and the scientific services sector.

As shown in Fig. 4b, the N_2O emissions caused by the local scale dominated in 10 sectors, namely transportation, wholesale and retail, hotel and restaurant, finance, real estate, commercial services, scientific services, resident services, education, and public management, ranging between 55.42 and 99.94 % of the total. The largest emissions at the local scale were associated with the real estate, finance and public management sectors, accounting for >97 % of the sectoral totals. Domestic imports for local production was the largest emissions source in 4 sectors (information services, social welfare, and culture and sports).

In general, the local scale was the main source of CH_4 and N_2O emissions for most services. Therefore, emissions control policies should focus on local production and consumption. For example, heat is an inevitable service demand in the winter in Beijing. However, heat is mainly produced from coal combustion, which causes CH_4 and N_2O emissions. Therefore, emissions control policies can be proposed that focus on the production process, such as subsidies that encourage heating enterprises to use geothermal heating sources. As another example, urban population growth increases the consumption demand of the transportation sector. However, most current vehicles are powered by gasoline or diesel fuel; thus, increased travel by these vehicles increases N_2O and CH_4 emissions. Therefore, emissions control policies should focus on the consumption process, such as price subsidies for electric cars or community education for short trips with bicycles. Because the current CO_2 mitigation policies also focus on the local scale, CH_4 and N_2O emission reductions can share some locally existing CO_2 mitigation policies; however, the sectoral differences in CH_4, N_2O, and CO_2 emissions must be noted.

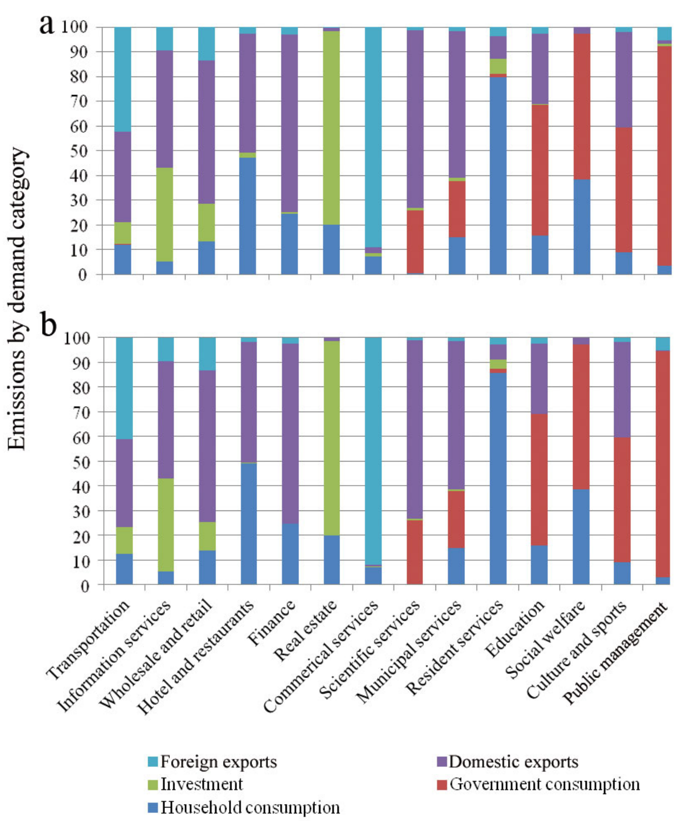

Fig. 5. (a) CH_4 and (b) N_2O emissions in 5 demand categories (foreign exports, domestic exports, investment, government consumption, and household consumption)

Moreover, some service sectors are associated with emissions in other regions in China or in foreign countries. Thus, some CH_4 and N_2O emissions in other regions in China or in foreign countries are caused by meeting the demand of local service production in Beijing. The central government of China should note the inter-regional emissions and fairly distribute the responsibilities for emission reductions in each province. Similarly, the distribution of the national responsibility for GHG emissions reduction should consider the GHG emissions embodied in international commodities and service trading.

3.4. Total emissions by demand category

Sectoral total CH_4 and N_2O emissions were divided into 5 demand categories (household consumption, government consumption, investment, domestic exports, and foreign exports), as shown in Fig. 5.

Sectoral emissions of CH_4 and N_2O exhibited similar trends. Although the proportions of the demand categories contributing to total sectoral emissions differed slightly between CH_4 and N_2O emissions, domestic exports dominated the production activities associated with information services, wholesale and retail, finance, scientific services, and municipal services. Government consumption dominated education, social welfare, culture and sports, and public management. Household consumption dominated resident services. Investment dominated real estate. Foreign exports dominated transportation and commercial services for both CH_4 and N_2O emissions. In the hotel and restaurant sector, domestic exports dominated CH_4 emissions, accounting for 48.18 % of the sectoral total, and household consumption dominated N_2O emissions, accounting for 49.20 % of the sectoral total.

Table 6. Summary of the estimates of Beijing's greenhouse gas (GHG) emissions generated by the different services considered in our study. CO_2-eq: CO_2-equivalent

Year	Source	Model specifications	Model assumptions	Type of GHG	Total emissions	Units
2002	Zhou et al. (2010)	Single-region ecological input–output model describing the sectoral embodiment (direct plus indirect endowment) of GHG emissions	One scale, imported commodities or services have the same emission intensities as local ones	CO_2	197720.36[a]	1000 t
				CH_4	7092.14[a]	1000 t CO_2-eq
				N_2O	836.89[a]	1000 t CO_2-eq
2007	Guo et al. (2012a)	Single-region input–output model describing the sectoral embodiment (direct plus indirect endowment) of GHG emissions	One scale, imported commodities or services have the same emission intensities as local ones	CO_2	94500.00	1000 t
				CH_4	2480.00	1000 t CO_2-eq
				N_2O	881.00	1000 t CO_2-eq
2007	Guo et al. (2012b)	Single-region input–output model describing the sectoral embodiment (direct plus indirect endowment) of CO_2 emissions	One scale, imported commodities or services have the same emission intensities as local ones	CO_2	Unable to obtain[b]	
2007	Chen et al. (2013)	Single-region multi-scale input–output model for sectoral embodied emissions	Three scales, different emission intensities between imported and local commodities or services	CO_2	Unable to obtain[b]	
1995	Zhang et al. (2013)	Direct emission calculation based on the energy-related carbon emission coefficient	One scale, imported commodities or services have the same emission intensities as local ones	Carbon	2374.00	1000 t
2000				Carbon	3248.00	1000 t
2005				Carbon	6534.60	1000 t
2009				Carbon	8622.20	1000 t
2000	Wang & Yang (2016)	Single-region input–output model for the total emissions generated from residential consumption	One scale, imported commodities or services have the same emission intensities as local ones	Carbon	10500.00	1000 t
2002				Carbon	20120.00	1000 t
2007				Carbon	25840.00	1000 t
2010				Carbon	21350.00	1000 t
2010	Ge & Lei (2014)	Single-region input–output subsystem model for the sectoral total emissions generated from a group of sectors	One scale, imported commodities or services have the same emission intensities as local ones	Carbon	11554.00	1000 t
2010	This study	Single-region, multi-scale input–output subsystem model for the sectoral total emissions generated from a group of sectors	Three scales, different emission intensities between imported and local commodities or services	CH_4	5641.25	1000 t CO_2-eq
				N_2O	674.05	1000 t CO_2-eq

[a]Emissions based on the Beijing input–output table from 2002 and on the GHG emission intensities from the different sectors of the Beijing economy in 2002

[b]Authors only provided emission figures

4. DISCUSSION

Table 6 provides the models and estimates of Beijing's GHG emissions. A comparison between the studies listed in the table and our study indicates that few studies have focused on GHG emissions from individual service sectors. Most studies have focused on the emission volumes of all sectors, which can help us understand the overall emission trends and propose emission mitigation measures from the perspective of the entire economy (e.g. reduce the proportion of pollution-intensive industries). However, services have been dominant in Beijing's economy, accounting for 77.90% of the total GDP in 2014 (BMBS 2015). Based on the shift from a manufacturing-dominant to a service-dominant economy in Beijing, our discussion of GHG emission mitigation should focus on services rather than on the whole economy. Moreover, because the marginal abatement cost of industrial emissions has become high in Beijing, emission reduction has focused on service-based and residential consumption (Wu et al. 2015). Therefore, it is necessary to analyze and understand the paths of GHG emissions from the services in Beijing, which can help the government determine appropriate emission reduction policies. For example, our study revealed that industrial production processes that provide intermediate inputs for the services (e.g. electricity production for the hotel and restaurant sector) and the consumption processes of the services (e.g. residential consumption of transportation) are the major emission sources.

CH_4 and N_2O emissions are lower but more harmful than CO_2 emissions in terms of their effect on 'greenhouse warming'. In metropolitan areas such as Beijing, large amounts of solid waste and vehicles due to the large population and high incomes have significantly increased CH_4 and N_2O emissions. Unlike many studies on emissions, our analysis focused on CH_4 and N_2O emissions, according to the features of the Beijing metropolis. Because of the different sources of CH_4, N_2O, and CO_2, emission reduction measures should focus on different sectors and processes for different GHG emissions (Muylaert de Araujo et al. 2007). For example, among the services in Beijing, the largest CO_2 emission was observed in the transportation sector in most studies (Guo et al. 2012b, Chen et al. 2013, Ge & lei 2014), while the greatest CH_4 and N_2O emissions were from the information services sector and the culture and sports sector. Because the CH_4 and N_2O emissions from some sectors, such as transportation, were larger than the sectoral average emissions, some CO_2 emission mitigation measures could also be used for CH_4 and N_2O emissions reduction. However, the major objectives of emission mitigation policies on CH_4 and N_2O emissions are different from those on CO_2 emissions. Our study provided the key sectors and their individual emission paths, considering direct and indirect emissions, for CH_4 and N_2O emissions reduction. These results can help the government identify the policies that can be applied to CH_4 and N_2O emissions reduction and special policies that should be created for CH_4 and N_2O emission mitigation within the existing policy framework of CO_2 emissions reduction.

Among studies on CH_4 and N_2O emissions in Beijing, estimations varied. This may be because of different years, model assumptions, and data sources. Our study is based on the input–output extension table of Beijing in 2010, while others used the input–output tables from 2002 (Zhou et al. 2010) or 2007 (Guo et al. 2012a). Moreover, our study constructed a 3-scale input–output model for estimation, which assumed that the emission intensities at the local, domestic, and foreign scales were different. This makes our estimations closer to actual emissions than the estimations that used the single-region assumption. Based on our 3-scale model, we can determine the scale that emitted the largest amount of CH_4 or N_2O emissions among the local, domestic, and foreign scales, helping policymakers to determine the key scale for emissions regulation, as noted by Chen et al. (2013) regarding the advantage of multi-scale models. Finally, what is included as emission sources can also influence the estimation. For example, if the emission sources only include fossil fuel combustion, estimates would be smaller than estimates that include more sources, such as agriculture activities, fugitive emissions, or waste.

To separate and identify the CH_4 and N_2O emissions from individual sectors, a subsystem is established based on this 3-scale input–output model. Based on this subsystem, we can highlight the different roles played by different services associated with total emissions at local, domestic, and foreign scales. For example, for each service, we can determine the largest effect, the pull (denoted by the EC component), or the push (represented by the INC component). For a sector, if the push effect is larger than the pull effect, the sector should be given a relatively lenient emission reduction target, because most of its emissions support other production activities. Emissions mitigation measures should focus on emission sources, such as improving the efficiency of fossil fuel combustion. For a sector, if the push effect is smaller than the pull effect, a relatively harsher regulation should be imposed. Emissions mitigation measures should encourage the sector to reduce the use of high-polluting intermediate goods and increase the use of clean alternative intermediate goods. Therefore, identifying the services' roles may help determine their responsibilities regarding emissions reduction.

5. CONCLUSIONS

This study presented a 3-scale input–output subsystem model for CH_4 and N_2O emissions from the service sector in the Beijing economy in 2010 based on CH_4 and N_2O emission intensities at the local, domestic, and foreign scales. Calculations and analyses provided 4 types of emission information: sectoral direct and total emissions associated with the service sectors; the roles of 4 components (DLC, ITC, INC, and EC) in the total emissions generated by demand for services; 3 scales (local, domestic, and foreign scales) of emissions generated by demand for services; and emissions generated by 5 demand categories (household consumption, government consumption, investment, domestic exports, and foreign exports).

Compared with direct emissions, indirect CH_4 emissions due to the pull effect from services to other sectors were not significant. However, direct emissions of CH_4 were of major importance and should receive greater attention from policymakers. For N_2O emissions, the pull effect of the service sectors played a greater role than did direct emissions.

For the 4 components of total emissions, the DLC was the most significant contributor to sectoral CH_4 and N_2O emissions. This suggests that for most services, emissions were caused primarily by final consumption of the services. CH_4 and N_2O emission control policies in Beijing should consider final consumption structure upgrades and different pollution mitigation strategies tailored to the development of different sectors.

The results of the 3-scale analysis suggest that CH_4 and N_2O emission reduction policies should focus on local production and consumption, because the local scale was the main emission source for most services. Some service sectors' emissions occurred in other regions of China or in foreign countries, suggesting the need for interregional and interstate cooperation strategies (e.g. emissions trading) for emissions mitigation.

Finally, the contributions of domestic exports and government consumption to sectoral CH_4 and N_2O emissions were of relative importance for most services. This may be related to the domestic service trade between Beijing and other regions in China and public administration needs in the metropolis of Beijing.

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