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Changing patterns and determinants of infrastructures' material stocks in Chinese cities

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ABSTRACT

Quantifying the changing patterns and determinants of material stocks (MS) is important for understanding the interplay between socioeconomic development and environment conservation, and for addressing the challenges in sustainable development. This paper conducts a MS accounting for 10 materials in 6 major infrastructures in Beijing, Tianjin and Shanghai, and probes into the driving factors behind the change within the 1978–2013 period through a logarithmic mean divisia index decomposition method. The results suggest that MS changes through a rapid enhancement in the 1980s, a steadily growth in the 1990s, and an acceleration after the 2000s. A relative decoupling phenomenon was detected in the development of economy and MS, which was largely caused by the decline of MS intensity. The policy implications include paying more attentions to the improvement of MS efficiency especially in buildings, substituting for less energy-intensive construction materials, controlling the extensive urban sprawl, and raising the population density.

1. Introduction

As an important bridge linking human society and natural environment, infrastructures are the fundamental facilities and systems that provide social and economic services to the human society, and at the same time large storehouses that contain a great amount of metal and nonmetallic materials extracted from environment. In order to meet the demands of economic development and human wellbeing improvement, infrastructures are growing to unprecedented volumes, and exerting ever-greater pressures on resource and energy depletion. And this is especially true in China. During the last decades, the increasing investment on buildings, roads, rails, water and gas pipelines has resulted in a soar of infrastructure level accompanied by the rapidly expanding cities and growing economy. Nearly half of the new buildings in the world were built in China annually for the last decade (Fernandez, 2007). The total lengths of roads and railways have been tripled and doubled between 1990 and 2013, reaching 0.3 and 0.1 million kilometers in 2013 respectively (NBS, 2014). However, the infrastructure development was highly resource intensive. For examples, China's steel consumption in 2012 accounted for 46% of the world total, in which 57% was consumed by the construction sector (Zhu and Lee, 2012; World Steel Association, 2013). The embedded CO_2 emission in China's infrastructures in 2008 was 26.6 billion tons, which was much higher than that of USA (18.1 billion tons) and other developed countries (Müller et al., 2013). In a resource-constrained era, material flows should be minimized, and maintenance of stocks becomes the central purpose of economic activity, and will largely affect the recycling of materials (Boulding, 1966; Pauliuk et al., 2012). As a premise for understanding the interaction between socioeconomic activities and environment conservation, and managing the resources efficiently so as to address the challenges of sustainable development, the investigation of changing patterns and determinants of MS, especially in the developing countries, would be of great importance.

Building on the pioneer works on material metabolism in the 1960s (Wolman, 1965), there are increasing interests in the quantification of either specific metals (e.g. iron, copper, aluminum) or bulk materials (e.g. concrete, cement, timber) of infrastructures, and the analysis of their interplay with human society's development and environmental change (Müller et al., 2014). In Table 1, we summarize the studies on MS of infrastructures in the last decade with respect to their research scales, accounted materials, methods, case study area and time range. Obviously, existing studies were carried out dominantly on country level, while those global, region, and city scaled analyses are relatively insufficient. For the

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Table 1
Recent studies on MS in infrastructures.

Scale	Materials analyzed	Methods	Study area & time range	Source
Global	Aluminum, steel, cement in residential buildings, transport, industry and other sectors	Top-down	Global 2008	Müller et al. (2013)
	Copper in buildings, transportation, power infrastructures, and others	Bottom-up	Global 1990–2100	Gerst (2009)
	Steel in buildings, civil engineering, and others	Top-down	42 countries 1980–2050	Hatayama et al. (2010)
Country	Concrete in residential buildings	Bottom-up	The Netherlands 1900–2100	Müller (2006)
	Construction materials in buildings	Bottom-up	Germany 1918–2025	Schiller (2007)
	Construction materials in buildings	Bottom-up	Switzerland 1900–2000	Lichtensteiger and Baccini (2008)
	Concrete and wood in residential buildings	Bottom-up	Norway 1900–2100	Bergsdal et al. (2016)
	Construction materials in buildings	Top-down	Japan 1970–2000	Hashimoto et al. (2009)
	Construction materials in roads, buildings, and water pipelines	Bottom-up	Japan 1965–2005	Nagaoka et al. (2009)
	Steel in buildings	Bottom-up	China 1900–2100	Hu et al. (2010a)
	Construction materials in buildings	Bottom-up	China 1950–2050	Huang et al. (2013)
	Construction materials in buildings and transport networks	Bottom-up	China 1950–2050	Shi et al. (2012)
	Construction materials in water pipelines	Bottom-up	China 1978–2050	Hou et al., 2015
	Construction materials of major infrastructures	GIS	Japan 1945–2010	Tanikawa et al., 2015
Region	Steel in buildings and transport infrastructures	RS	30 provinces in China 1992–2008	Liang et al. (2014)
	Construction materials in major infrastructures	Bottom-up	30 provinces in China 1978–2008	Han and Xiang (2013)
City	Construction materials in major infrastructures	GIS	Manchester city center, UK 1984–2004; Wakayama city center, Japan 1855–2004	Tanikawa and Hashimoto (2009)
	Construction materials in residential buildings	Bottom-up	Beijing, China 1949–2008	Hu et al. (2010b)
	Concrete, iron, plastics in water pipelines	Bottom-up	25 cities in 5 countries 2008	Pauliuk et al. (2014)

reasons, lack of comprehensive, comparable and consistent historical data on infrastructures and their lifetime distribution could be the major obstacle. Methodologically, material flow analysis (MFA) is the most widely accepted and standardized approach in material metabolism study (Gerst, 2009; Krausmann et al., 2014). It analyses the MS through the historical inflow and outflow data, such as import, trade, export, and consumption statistics (Müller et al., 2014), and can be further divided into top-down and bottom-up approaches. The former one uses material inflow data to estimate the addition to stocks within a time span, and is usually applied in the economy-wide metabolism research (For examples, Hashimoto et al., 2009; Müller et al., 2013). The latter approach estimates MS through the detailed statistics of infrastructures, such as road length, and floor space of residential buildings, and their correspondent material intensity (For examples, Müller, 2006; Han and Xiang, 2013). Moreover, with the spatial analysis techniques being widely used in environmental studies, remote sensing (RS) and geographical information system (GIS) approaches are also introduced in estimating MS of infrastructures. Usually, RS and GIS are used either to collect the nighttime light data as a proxy to represent the MS changes (Liang et al., 2014), or to compile local infrastructure information for stock accounting (Tanikawa and Hashimoto, 2009; Tanikawa et al., 2015). On the other hand, with the urbanization proceeds, cities will accommodate about 70% of total population in the world in 2050. They will definitely play a dominant role in contributing to environmental degradation, but at the same time could be the key for solving the problems (The World Bank, 2010). Thus the studies on MS and those policies to reduce the impacts of socioeconomic development on resource depletion at city level are becoming increasingly needed.

To complement the knowledge of city-scaled MS especially in developing countries, we choose Beijing, Tianjin and Shanghai, the three highly urbanized municipalities for a case study. The three cities totally had 60 million populations in 2013, and generated about 10% of China's GDP. Their infrastructure levels are also high comparing to other cities in China. For example, the length of water pipelines per capita in Beijing, Tianjin and Shanghai reached 1.3, 2.2 and 2.3 m respectively in 2013, while the national average was only 0.4 m/capita. Through the quantification of MS in major infrastructures between 1978 and 2013, and the investigation of their driving forces, we aim at making two specific contributions to the MS and sustainable resource management issues in China. Firstly, we performed a comprehensive and up-to-date accounting of MS covering 6 major infrastructures and 10 types of metal and nonmetallic materials, while that have not been fully investigated in the existing literatures. Secondly, the exploration and comparison of dynamics and determinants of MS in the three highly urbanized Chinese cities would provide experiences and policy implications for sustainable resource utilization in those rapidly urbanizing cities, where a great amount of infrastructures are being built.

2. Data and methods

2.1. Accounting framework and data

As shown in the framework of Fig. 1, six types of infrastructures including residential and non-residential buildings, roads, railways, gas pipelines, and water pipelines are set as the objectives. Statistical data regarding the size of their sub-types, such as floor area of newly built residential and non-residential buildings in both urban and rural areas, length of road systems consisting of highway and road class I to class IV, railways of both wooden and concrete ties, are collected mainly from statistical yearbooks, such as "Comprehensive Statistical Data and Materials On 60 Years of New China" (NBS, 2009), and "China Statistical Yearbook" (NBS, 1996–2014). Totally 10 types of metal and nonmetallic construction materials are considered for accounting, as they constitute a large proportion of the total materials in infrastructures (Eurostat, 2012). Material intensity of each type of infrastructure and material, in the unit of metric kilogram per square meters for buildings, kilogram per kilometers for roads, railways and pipelines, are compiled from the literatures, design codes, among others.

2.2. MS estimation

A bottom-up MFA method is adopted for MS accounting. The stock at the year-end is estimated as the remained old stock plus the newly built stock, as illustrated in Eq. (1).

$$MS_i^t = MS_i^{t-1} \cdot \left(1 - DEM_i^t\right) + \Delta MS_i^t \qquad (1)$$