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Material metabolism and lifecycle impact assessment towards sustainable resource management: A case study of the highway infrastructural system in Shandong Peninsula, China

Zhen Guo [a], Honghua Shi [a], Peidong Zhang [b], Yuan Chi [a], Aiping Feng [a, *]

[a] Research Center for Islands & Coastal Zone, First Institute of Oceanography, State Oceanic Administration, 6 Xianxialing Road, Qingdao 266061, China
[b] Qingdao University of Science and Technology, College of Environment and Safety Engineering, Qingdao 266042, China

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ABSTRACT

The accelerated construction of general infrastructure with global urbanization necessitates the massive input of materials. The huge material input and waste output throughout the infrastructure's lifecycle have led to severe resource depletion and the accumulation of potential environmental risks. The systematic evaluation of typical infrastructure stocks is very important to study regional resource availability and explore sustainable development modes under intensive human activities. In this study, we build a material stock model for a highway system that is based on the theory of material metabolism. We analysed the scale and structures of the stock and its lifecycle effects in the Shandong Peninsula. The following results are shown: 1) the total material stock in the entire highway system was 1933.57 Mt in 2013, and the six materials with the largest inputs were stones, fly ash, lime, cement, mineral powder and asphalt, which together comprised 99.8% of the stocks; 2) the material-driven impacts mainly originated from production and construction stages, of which the main damage types were fossil fuels, inhalable inorganics, climate change and land use; 3) the end products for highway construction were mainly supplied by Shandong itself. The average transport distance for different materials ranged from 25 to 174 km. Steel, stone and asphalt had a longer transport distance than others; and 4) the top three parameters that largely affected the stocks were the road length, roadway structure, and cross-sectional subgrade structure. The inputs could be largely reduced by appropriately adjusting the structures of roadways and subgrades in low-class roads.

1. Introduction

In addition to the acceleration of the global economy and aggravation of human activities, severe resource pressure and resulting eco-function deterioration are becoming major inhibitors against regional development (Hoekstra and Wiedmann, 2014). China's economy in 2011 was achieved at the cost of 25.2 billion tons of raw materials, which exceeded the summation of the 34 members of the Organization for Economic Co-operation and Development (OECD) (Mathews and Tan, 2016). In particular, the accelerated construction of general artificial infrastructure, including roads and buildings, necessitates the massive input of materials, which accumulate in the form of stocks and lead to the shortage of regional resources and the formation of potential environmental risks (Du Plessis and Brandon, 2015). If no appropriate measures are taken, such large-scale natural resource input and waste output would impose tremendous stress on China and even the entire world. The systematic evaluation of typical infrastructure stocks during accelerated urbanization, especially in developing countries such as China, is very important to study the regional resource environmental capability and explore sustainable development modes under intensive human activities (Huang et al., 2013).

However, the forms and paths of material migration and conversion within social systems refer to a different type of complexity compared to that under natural conditions (Wang and Ou Yang, 2012). Researchers have been attempting to quantitatively analyse and evaluate the human-natural ecosystem from a holistic perspective. In this process, the concept of "metabolism" from idiobiology has gradually been trans-dimensionally introduced to

* Corresponding author.
E-mail address: fengap@fio.org.cn (A. Feng).

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study this complex ecosystem. Researchers aim to study the formation mechanisms of resource and environment issues during the development of different metabolic systems (e.g., regions, cities, industries, and families) by analysing the static or dynamic characteristics of material and energy, thereby proposing corresponding regulation strategies (Kennedy et al., 2007).

1.1. Brief review of material metabolism and stock research

The input, storage and output processes of material and energy flows in social systems have attracted increasing attention following the proposal of "Urban Metabolism" and "Anthropogenic Metabolism" in the 1960s and 1990s (Baccini and Brunner, 2012; Wolman, 1965). Researchers intend to determine the solutions to optimize or recombine processes and to explore novel production and consumption methods by characterizing all the stages in these lifecycles.

The theory and connotation of material metabolism have been gradually expanded in the past 50 years and have become important methods for the quantitative analysis of human ecosystems (Zhang, 2013). Significant progress has been made in the following aspects: 1) urban metabolism according to cities or city agglomerations, such as units, which is conducted across different regions and different development levels (e.g., Brussels, Hong Kong, and Toronto) and provides many case studies for the sustainable development modes of eco-cities (Duvigneaud and Denayer-de Smet, 1977; Sahely et al., 2003; Warren-Rhodes and Koenig, 2001); and 2) industrial metabolism within specific domains, which involves the metabolic processes of different departments, including household consumption, building systems, waste, and industrial processes, thus expanding the research fields of material metabolism (Ayres and Simonis, 1994; Hu et al., 2010; Liang and Zhang, 2012; Moll et al., 2005).

Global urbanization studies have begun to focus on massive resource flows from the lithosphere into the anthroposphere, which gradually accumulate within human society (Baccini and Brunner, 2012). Quantitative research on material stocks in social systems has become increasingly popular in the new millennium, which has bloomed into one of the mainstream methods to evaluate resource appropriation and eco-environmental effects (Gerst and Graedel, 2008). Thus far, stock research involves the material storage of scale-varying metabolic subsystems in the social system, including elements (e.g., steel and phosphorus), potential environmental risk products or durable goods (e.g., PVC), municipal infrastructure (e.g., building systems, road systems, and pipeline systems), and so on (Chen and Graedel, 2015; Hirato et al., 2009; Kleijn et al., 2000; Kohler and Hassler, 2002; Lederer et al., 2014). Additionally, stock studies are increasingly combined with geospatial characterization that is based on GIS (Wu et al., 2016).

1.2. Highway system: metabolic features for a typical infrastructure system

Highways, which are a major component of traffic infrastructure, serve as the under-structure of regional economic development that bears material, energy and population flows. By the end of 2015, the total highway length in Mainland China was 4,465,600 km, including a total expressway length of 125,373 km, which surpassed that in the US to become number one in the world (MOT, 2016). As in other countries, highway construction in China reduces the time cost of domestic traffic, efficiently optimizes the industry layout and accelerates China's reformation and development processes.

However, the entire lifecycle period of highways, a netlike corridor system with high human interference, involves many resource-related and eco-environmental problems, which have recently boosted the development of inter-disciplines such as road ecology (Forman, 2003). Especially from a material metabolism perspective, road systems refer to huge material use and energy consumption and are regarded as one of the three most important infrastructural stocks after buildings and pipelines (Huang et al., 2016). Road networks are expanding annually and have formed an extra-large-scale durable infrastructure with a long lifecycle, in addition to the implementation of pavement upgrades and renewal projects. The in-use stocks that have accumulated in current systems would finally pass the usage stage, be transformed into waste and be discharged into the environment. Identifying the scale, composition and potential environmental risks of these intensive artificial stock systems should provide new clues to study the coordination mechanism between human construction activities and resource environment system feedback and to explore a more balanced means of regional sustainable development.

Because of data unavailability, plenty of existing studies are based on a top-down concept that mainly relies on statistics with low accuracy rather than deep investigations of the "stock black box" (Dall'O' et al., 2012). Additionally, few research projects have focused on road systems (Guo et al., 2014; Wen and Li, 2010).

In this study, we probe the standards and procedures of highway engineering and thereby build a material stock model of the highway system based on the perspective of urban metabolism. We studied the material stock of the highway system in the developing Shandong Peninsula, which is located in East Chain's coastal zone, and its environmental impacts throughout its lifecycle to evaluate the comprehensive environmental risks and provide a feasible means to manage the resource of this infrastructure system.

2. Methods and materials

2.1. Metabolic modes and hierarchies of a highway network system

The material metabolism of a highway system can be divided from a lifecycle perspective into a mineral exploitation & transport stage, a raw material production & processing stage, a construction stage, an operation & maintenance stage, and a dismantling & waste disposal stage. At the end of this lifecycle, some of the waste (e.g., asphalt, curbs, and guardrails) that is produced during road renovation and maintenance can be reused after processing. Highway systems are a type of metabolism system that is characterized as being open and dynamic. During its entire lifecycle, this system exchanges material and energy with regional or even global ecosystems, thereby maintaining its normal operation (see Fig. 1).

The construction criteria of roadway and cross-sectional structures vary between classes. Thus, an appropriate and feasible stock classification system is necessary, which would affect the final stock results to some extent. Each country has its own specific highway classification system. The highways in Mainland China are generally divided by traffic volume into five classes: Expressway (motorway), Class I highway, Class II highway, Class III highway, and Class IV highway (MOT, 2015). These five classes can be narrowed to three categories according to similarities in their designing demands: Expressway, Class I & II highways, and Class III & IV highways (see Table 1).

2.2. New model to calculate the stock of a highway system

Gerst and Graedel proposed two stock study systems from an economic perspective: the top-down method and the bottom-up method (Gerst and Graedel, 2008). The bottom-up method was used in this study, which deconstructs a stock system into stock units and recombines material stocks by identifying the