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Expansion of environmental impact assessment for eco-efficiency evaluation of China's economic sectors: An economic input-output based frontier approach

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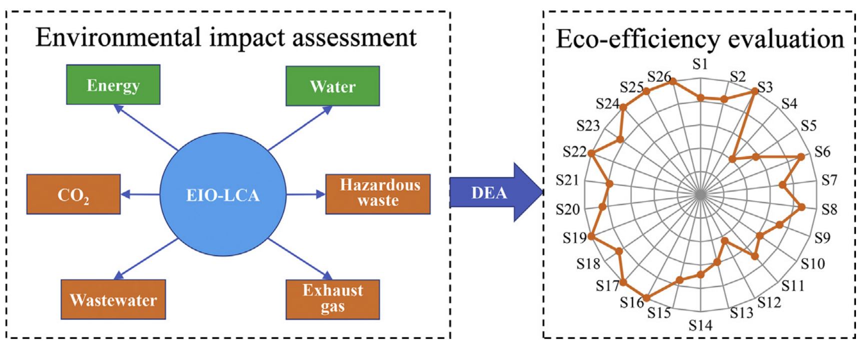
HIGHLIGHTS

- EIO-LCA and DEA are combined to assess eco-efficiency of China's economic sectors.
- The embodied environmental impact transfer between sectors is tracked in detail.
- Electricity and Construction sectors are respectively the largest exporter and importer.
- Eco-efficiency results are not optimistic and vary among sectors.
- Key sectors to control impacts and improve eco-efficiency are uncovered.

GRAPHICAL ABSTRACT



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ABSTRACT

Due to the increasing environmental burdens caused by dramatic economic expansion, eco-efficiency indicating how efficient the economic activity is with respect to its environmental impacts has become a topic of considerable interest in China. In this context, Economic Input-output Life Cycle Assessment (EIO-LCA) and Data Envelopment Analysis (DEA) are combined to assess the environmental impacts and eco-efficiency of China's 26 economic sectors. The EIO-LCA results indicate that Electricity Production and Supply sector is the largest net exporter in energy usage, CO_2 emission and exhaust emission categories, while Construction sector is the largest net importer for five impact categories except for water withdrawal. Moreover, Construction sector is found to be the destination of the largest sector-to-sector environmental impact flows for the five impact categories and make the most contributions to the total environmental impacts. Another key finding is that Agriculture sector is both the largest net exporter and the greatest contributor for water withdrawal category. DEA results indicate that seven sectors are eco-efficient while over 70% of China's economic sectors are inefficient and require significant improvements. The average target improvements range between 23.30% and 35.06% depending on the impact category. Further sensitivity analysis reveals that the average sensitivity ratios vary from 7.7% to 15.7% among the six impact categories, which are found to be negatively correlated with their improvement potentials. Finally, several policy recommendations are made to mitigate environmental impacts of China's economic sectors and improve their eco-efficiency levels.

1. Introduction

China's reform and opening-up policy launched in 1978 has helped the country achieve remarkable economic growth over the past three

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decades. It is calculated that China's Gross Domestic Product (GDP, in constant price) has increased by >29-fold from 1978 to 2015 (NBSC, 2016). However, for a long time, China's economic development has followed an extensive mode of growth which has resulted in enormous increases in resource consumption. For instance, China's energy consumption in 2015 was 7.5 times as much as that of 1978 (NBSC, 2016). In addition, a series of environmental issues such as soil erosion, air contamination and global warming triggered by the unsustainable economic growth mode are also faced by China (Xing et al., 2017). In light of the tremendous challenges from resources and environment, ecological improvement has been emphasized as a firm pursuit of China's development in the 13th Five-Year period (2016–2020) Plan (NDRC, 2016). In addition, at the 19th National Congress of Communist Party of China, insistence on the harmony between human and nature was proposed as the foundation of China's modernization development (SCPRC, 2017). In this context, the key to China's sustainable development lies in the harmonization of economic development and ecological conservation to maximize economic outputs with minimal environmental impacts. Therefore, eco-efficiency analysis of Chinese economy should be of considerable concern.

Due to the fact that environmental impacts are embodied in goods and services traded between sectors in the industry network, the assessment of total environmental impact (direct plus indirect) is the key for the eco-efficiency evaluation from life cycle point of view. This analysis can be carried out based on input-output tables which cover a wide range of economic transactions taking place between sectors of an economy (Leontief, 1936, 1970). In this regard, Economic Input-Output based Life Cycle Assessment (EIO-LCA) is usually applied to perform environmentally extended input-output analysis which links economic transactions to the environmental burdens they cause (Hendrickson et al., 2006). There is a large body of literature on applying EIO-LCA to uncover total environmental impacts of regions or sectors, such as energy consumption (Chang et al., 2010; Liu et al., 2012; Yang et al., 2014; Chen et al., 2017a), water withdrawal (Blackhurst et al., 2010; Dong et al., 2014; Serrano and Valbuena, 2017; Antonelli et al., 2017), carbon dioxide (CO_2) emission (Li et al., 2016; Kumar et al., 2016; Zhang and Wang, 2016; Chen et al., 2017b), and other pollutants emission (Rosenblum et al., 2000; Liu and Wang, 2017; Chen et al., 2017c). However, except for a few studies (e.g. Chen et al., 2017c), most of them have seldom analyzed the trade-offs between economic development and environmental impact, focusing efforts only on quantifying the environmental dimension of sustainability in isolation from the economic one.

Eco-efficiency, firstly proposed by Schaltegger and Sturm (1990), often serves as a measurement of the coordination degree between economic development and ecological conservation. Accordingly, eco-efficiency is usually defined as the ratio of economic output to the overall ecological input, which indicates how efficient the economic activity is with respect to its environmental impacts (Schmidheiny and BCSD, 1992). Data Envelopment Analysis (DEA, Charnes et al., 1978) is usually employed to estimate eco-efficiency in which economic value is often taken as the output, while the inputs are various environmental impacts. Literature on eco-efficiency assessment with DEA is intensive (see Table 1). From this table, we can observe that the research objects mainly included OECD countries (Camarero et al., 2013; Robaina-Alves et al., 2015), provincial regions of China (Huang et al., 2014; Ren et al., 2016; Yang and Zhang, 2018) and provincial industrial sectors of China (Zhang et al., 2008; Yang et al., 2012; Zhang et al., 2017). In addition, it is also found that energy usage, water withdrawal, CO_2 emission, solid waste generation, wastewater discharge and exhaust emission are the commonly considered environmental impacts, which are thereby taken into consideration by this study. Nevertheless, these studies have provided little insight on how impacts are generated at the sector level (i.e. which sectors are ultimately responsible for the impact caused), since they are based on production-based data.

The combined application of LCA and DEA provides a tool for the comprehensive assessment of the environmental impacts and operational performance of multiple DMUs (Lozano et al., 2009). Literature on the application of LCA + DEA to eco-efficiency evaluation is abundant (Vázquez-Rowe et al., 2012; Avadí et al., 2014; Ullah et al., 2016; Masuda, 2016; Martín-Gamboa et al., 2017; Rebolledo-Leiva et al., 2017). For instance, Avadí et al. (2014) assessed eco-efficiency of the Peruvian anchoveta steel and wooden fleets by using the LCA + DEA approach. Also, Masuda (2016) utilized LCA + DEA methodology to evaluate the eco-efficiency of regional wheat production in Japan. The LCA + DEA can avoid the use of average inventory data (i.e., standard deviations are prevented) and enrich result interpretation through eco-efficiency verification (Iribarren et al., 2010). In addition, LCA + DEA results can lead to the identification of inefficient DMUs and to

Table 1
Summary of studies on measuring ecological efficiency with various input-output indicators.

Study	Decision making unit (DMU)	Ecological input		Economic output
		Resource consumption	Pollution emission	
Zhang et al. (2008)	30 Provincial industrial sectors of China, 2004	Water resource, raw mining resource, energy	Chemical oxygen demand (COD), ammonia nitrogen, sulphur dioxide (SO_2), soot, dust, industrial solid wastes	Gross industrial output (GIO)
Oggioni et al. (2011)	21 Cement-producing countries	Capital, labor, energy, raw materials	CO_2	Cement production
Yang et al. (2012)	30 Provincial industrial sectors of China, 1985, 1995, 2005, 2008	Energy, electricity, water	SO_2, wastewater, waste gas, solid waste	GIO
Camarero et al. (2013)	22 OECD countries, 1980–2008	–	CO_2, nitric oxides (NO_x), sulphur oxides (SO_x)	GDP
Huang et al. (2014)	30 Provincial regions of China, 2000–2010	Capital, labor, land, energy	COD, wastewater, exhaust gas, SO_2, dust, solid waste, smoke dust	GDP
Robaina-Alves et al. (2015)	26 European countries, 2000–2004 and 2005–2011	Capital, labor, fossil fuels, renewable energy	Greenhouse gas	GDP
Long et al. (2015)	31 Provincial cement manufactures of China, 2005–2010	Labor, capital, coal, electricity, clinker	CO_2	Cement production
Ren et al. (2016)	30 Provincial regions of China, 2000–2013	Energy, land, water, labor	Industrial waste water, COD, SO_2, soot, industrial dust, solid waste	GDP
Yu et al. (2016)	16 Provincial pulp and paper manufactures of China, 2010–2013	Water	Wastewater, COD, ammonia nitrogen	GIO
Yang and Zhang (2018)	30 Provincial regions of China, 2003–2014	Capital, labor, build-up land, water, energy	Solid waste, household refuse, SO_2, soot, industrial dust, wastewater	GDP
Zhang et al. (2017)	30 Provincial industrial sectors of China, 2005–2013	Capital, labor, energy	SO_2	GIO