# Decoupling environmental pressure from economic growth on city level: The Case Study of Chongqing in China

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**Abstract**: As cities represents the microcosms of global environmental change, it is very important for the global sustainable development by decoupling environmental pressure from economic growth on city level. In this paper, the municipality of Chongqing in China is employed as a case to show whether the decoupling of environmental pressures from economic growth has occurred in cities undergoing rapid economic growth; what is the level of decoupling; and what causes the observed degree of decoupling. Results show the following. (1) During the period of 1999-2010, decoupling from economic growth has been absolute for the emissions of $SO_2$, soot, and waste water, while it has been relative for total energy consumption, emissions of $CO_2$ and solid waste. (2) Compared with the period 2000-2005, decoupling level improved for all the six environmental pressures in the period 2005-2010. (3) Compared with China and other three municipalities of China, the overall decoupling level of Chongqing is above China's average while below those of Beijing and Shanghai. (4) During the period 1999-2000, technological change was the dominate factor for decoupling Chongqing's environmental pressure from economic growth, as it contributed 131.4%, 134.6%, 99.9%, 97.7%, 104.5% and 54.9% to the decoupling of total energy consumption, emissions of $CO_2$, $SO_2$, soot, waste water and solid waste, respectively; while economic structural change had very tiny effect to the decoupling of emissions of soot and $SO_2$, and it even had negative effect to that of total energy consumption, and emissions of $CO_2$ and waste water. Based on the above observations, we explain the difference in decoupling levels for different environmental pressures and suggest approaches for policy-makers on further promoting decoupling environmental pressure from economic growth.
**Keywords**: Decoupling; Environmental Pressure; Chongqing; Index Decomposition Analysis

## 1. Introduction

Decoupling environmental pressure from economic growth, i.e., breaking the link between 'environmental bads' and 'economic goods' (OECD, 2002), is one of the most critical priorities for

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sustainable development. There is an expanding body of literature on this topic and policy-makers and researchers worldwide continue to pay significant attention to its advancement (Arrow et al., 1995; Conrad and Cassar, 2014; De Freitas and Kaneko, 2011; Holdren, 2008; Wiedmann et al., 2015). Decoupling has been widely used as a policy objective by national, regional, and international institutions. For example, in the Organisation for Economic Co-operation and Development (OECD), decoupling environmental pressures from economic growth is adopted as the main objectives of the OECD Environmental Strategy for the first decade of the 21st century (OECD, 2002); in the European Union (EU), reducing the negative environmental impacts generated by the use of natural resources in a growing economy is the objective for the EU Thematic Strategy on the Sustainable Use of Natural Resources (EC, 2005); in the United Nations (UN), decoupling human well-being from resource consumption is at the heart of both the International Resource Panel's mandate and the Green Economy Initiative of the United Nations Environment Programme (UNEP, 2011). These policy objectives testify to the critical importance given by policymakers to research on the driving forces of decoupling.

Previous studies on decoupling environmental pressure from economic growth fall into two main streams. In the first stream, research has focused on applying various indicators (OECD, 2002; Tapio, 2005; Wang et al., 2013) to measure the decoupling level of different regions (Kovanda and Hak, 2007; Liang et al., 2013; Lu et al., 2014; Tachibana et al., 2008; Van Caneghem et al., 2010; Xue, 2012; Yu et al., 2013; Zhang et al., 2014; Zhu et al., 2013). Most of the studies in this avenue are at the national level and despite their importance, studies at the city level are an under researched area. Cities represent the microcosm of global environmental change (Grimm, 2008) and by current estimates account for more than 60% of global energy consumption and 75% of world greenhouse gas emissions (Satterthwaite, 2008). In 2050, the UN estimates that two-thirds of the global population will be urbanized (UN, 2008) and therefore the central role of cities in global environmental change will become more prominent.

In the second stream, the main research efforts have concentrated on exploring the driving forces of decoupling (Andreoni and Galmarini, 2012; De Freitas and Kaneko, 2011; Mazzanti and Zoboli, 2008; Liang et al., 2013; Lu et al., 2007; Ren and Hu, 2012; Sjöström and Östblom, 2010; Tang et al., 2014; Van der Voet et al., 2005). In these studies, the focus on decoupling economic growth from a single environmental pressure indicator is explored, e.g., carbon dioxide, domestic material consumption. However, by focusing on a single environmental pressure indicator, these studies may lead to what (Yang et al., 2012; Liang et al., 2012, 2013a, 2013b) describe as problem-shifting, i.e., the unintended aggravation of one environmental pressure resulting from the alleviation of another environmental pressure. In response to this problem, recent studies have attempted to examine multiple environmental pressures. For example, Liang et al. (2013a) explored the driving force of decoupling 31 environmental pressure indicators from economic growth in China by the method of structural decomposition analysis (SDA). However, this study is at the national level, and doesn't explain the difference in the decoupling level of different environmental pressures. On the city level, Van Caneghem et al. (2010) reported the decoupling level of eight environmental pressure indicators from the Flemish industry, but the driving force of decoupling is not examined. To our best knowledge, there are currently few studies on the drivers of decoupling economic growth for multiple environmental pressures at the city level.

Based on the above two research streams, there is a gap in the literature in studying the drivers of decoupling economic growth for a set of environmental pressure indicators at the city level. To contribute in filling this literature gap, we use Chongqing (one of China's major cities) as a case study to examine the decoupling of economic growth from multiple environmental pressures. Specifically, we examine the level of the decoupling of economic growth from six environmental pressure indicators and examine their driving forces by using the index decomposition analysis (IDA) method. The city of Chongqing was evaluated in this study based on its many advantages relevant to this research. Firstly, as a mega city with the most populous Chinese municipality, Chongqing has experienced rapid and significant changes in both its economic development and environmental pressures (Yu et al., 2015). Therefore, the city of Chongqing provides an important case study in examining the decoupling of environmental pressures from economic growth in Chinese cities. Secondly, Chongqing, as one of the four national central cities, is directly under the control of the Chinese central government, and therefore, in comparison to other cities, the economic and environmental data required for this research is more available and of higher quality.

This paper is structured as follows: Section 2 provides the general information of Chongqing. Section 3 introduces the methodology adopted in this study and reviews the steps taken for compiling the data. Section 4 reports the decoupling indexes for six environmental pressure indicators in Chongqing, evaluates the decoupling level by comparing them with other municipal cities of China, and analyses the driving forces of the decoupling phenomenon. Section 5 discusses the results of this study and provides some policy suggestions. A conclusion follows in Section 6.

## 2. Study site

Chongqing municipality, covering a land area of 82,403 $km^2$, is located between the North Latitude 28°10′–32°13′ and the East Longitude 105°11′-110°11′. Administratively, Chongqing is one of China's four direct-controlled municipalities, the other three are Beijing, Shanghai and Tianjin, and the only such municipality in inland China. As a major industrial city in China's southwest region, Chongqing is situated in the upper reach of the Yangtze River and also the upstream of the Three Gorges Dam[1] (as shown in Fig. 1). Because of this geographical location, the environmental issues of Chongqing are not only critical to Chongqing per se, but also critical to both the regions surrounding the Yangtze River and the Three Gorges Dam as it influences their ecological safety and sustainable development (Yu et al., 2015).

In 1997, the city of Chongqing was designated as the fourth national municipality directly managed by the Chinese central government. Because of the administrative attention, Chongqing has experienced very rapid economic development. For example, Chongqing's GDP increased by 269% during the period of 1999-2010. In 2010, Chongqing's GDP, GDP per capita, residential population, share of secondary industry respectively reached 793 billion CNY, 27,475 CNY, 28.8 million people, and 55%. However, along with the rapid economic development, environmental pressures also significantly increased in Chongqing, e.g., energy consumption increased by 218% during the period of 1999-2010. In this context, the decoupling of environmental pressure from economic growth is a very important issue of concern for the sustainable governance of Chongqing. Therefore, Chongqing is a good case study of decoupling environmental pressures from rapid economic growth at the level of cities in China.

[1] The Three Gorges Dam, a hydroelectric dam that spans the Yangtze River of China, in terms of installed generation capacity, is the world's largest power station. (http://en.wikipedia.org/wiki/Three_Gorges_Dam).

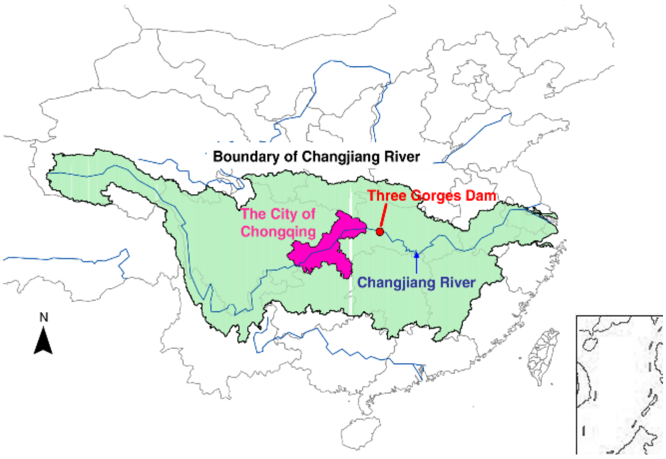


Fig. 1. Location of the Chongqing municipality and the Changjiang (Yangtze ) River Basin in China. (This figure is reproduced from Okadera et al. (2006))

## 3. Methods and data

### 3.1 Decoupling indicators

Researchers have developed various decoupling indicators to track the temporal changes in the relationship between environmental pressures and economic growth (OECD, 2002; Tapio, 2005; Wang et al. 2013). Among these, the most widely used indicator by researchers and policy makers is the Decoupling Index (DI) proposed by the OECD (2002). This indicator is defined as:

$$DI = 1 - \frac{M^t / Y^t}{M^0 / Y^0} = 1 - \frac{EPI^t}{EPI^0} \quad (1)$$

where the superscript $0$ and $t$ are the initial year and the end year for a certain period of time; $M$ and $Y$ are respectively the environmental pressure indicator and the gross domestic product (GDP) measured in constant prices; $EPI$ is the ratio of $M$ and $Y$, i.e., $EPI=M/Y$, indicating the overall environmental pressure intensity. By using eq. 1, three types of decoupling can be identified.

- **Absolute decoupling** occurs when $Y^t>Y^0$ and $M^t\leq M^0$, i.e., the economy grows while environmental pressure does not increase. In absolute decoupling, the value of DI is between 0 and 1.
- **Relative decoupling** occurs when $Y^t>Y^0$, $M^t>M^0$, and $Y^t/Y^0>M^t/M^0$, i.e., both the economy and environmental pressure grow, however the economy has a faster growth rate. In relative decoupling, the value of $DI$ is also between 0 and 1. And the less DI is, the lower relative decoupling is.
- **Coupling** occurs when $Y^t>Y^0$, $M_t>M_0$, and $Y_t/Y_0<M_t/M_0$, i.e., both the economy and environmental pressure grows, however the economy has a slower growth rate. In coupling, the value of DI is negative.

Among the three types of decoupling states described above, absolute decoupling is the most sought after state while coupling is the least sought after state and to be avoided in advancing economic development and environmental management.

### 3.2 Index decomposition analysis

Decomposition analysis is the most commonly used group of methods to quantify the driving force of environmental pressure indicators. Two popular techniques in this group which have been extensively used in energy and emissions are the structure decomposition analysis (SDA) (Su and Ang, 2012) and index decomposition analysis (IDA) (Liu and Ang, 2007). The former relies on input–output tables while the later uses aggregate data at the sector-level. As input-output tables are not compiled annually, the change of environmental pressure indicators can only be explained through the SDA approach with some time intervals. The IDA approach can overcome this problem by using only sector level data, which is available on an annual basis. Therefore, to develop a more detailed and temporally relevant understanding of the driving forces of environmental pressure indicator we use the IDA approach in this study.

By using the IDA approach, the overall environmental pressure intensity of a regional $EPI$ ($EPI=M/Y$) can be disaggregated into economic sectors as:

$$EPI=\frac{M}{Y}=\sum_{i=1}^{n}\frac{M_i}{Y_i}\frac{Y_i}{Y}=\sum_{i=1}^{n}T_iS_i \qquad (2)$$

where $M_i$ and $Y_i$ are respectively the environmental pressure and value added in sector $i$. And $n$ is the total number of economic sectors. Therefore, $T_i$ ($T_i=M_i/Y_i$) and $S_i$ ($S_i=Y_i/Y$) are the environmental pressure intensity and value added share in sector $i$, which respectively indicate technology and economic structure.

Using the method of logarithmic mean divisia index (LMDI) (Liu and Ang, 2007) the change of $EPI$ can be decomposed as:

$$\begin{aligned}
&\Delta EPI = EPI^t - EPI^0 = \Delta_T EPI + \Delta_S EPI\\
&\Delta_T EPI = \sum_{i=1}^{n} w_i(\ln T_i^t - \ln T_i^0)\\
&\Delta_S EPI = \sum_{i=1}^{n} w_i(\ln S_i^t - \ln S_i^0)\\
&w_i = (T_i^t S_i^t - T_i^0 S_i^0)/(\ln T_i^t S_i^t - \ln T_i^0 S_i^0)
\end{aligned} \qquad (3)$$

where $\Delta EPI$, $\Delta_T EPI$, $\Delta_S EPI$ are the change of $EPI$, the change of $EPI$ caused by $T$ and $S$, respectively. And $w_i$ is the weight co-efficient.

According to eqs. 1-3, the decoupling index can be rewritten as:

$$DI = 1-\frac{EPI^t}{EPI^0} = -\frac{\Delta EPI}{EPI^0} = -\frac{\Delta_T EPI}{EPI^0} - \frac{\Delta_S EPI}{EPI^0} = DI_T + DI_S \qquad (4)$$

where $DI_T$ ($DI_T$=-$\Delta_T EPI/EPI^0$) and $DI_S$ ($DI_S$=-$\Delta_S EPI/EPI^0$) denotes $DI$ induced by $T$ and $S$, respectively. Details for the proof of this equation is provided in supplementary material. Therefore, the contribution of $T$ and $S$ to the decoupling index, i.e., $C_T$ (technology effect) and $C_S$ (economic structure effect), can be calculated by:

$$\begin{aligned}
C_T &= \frac{DI_T}{DI}\times 100\%\\
C_S &= \frac{DI_S}{DI}\times 100\%
\end{aligned} \qquad (5)$$

From the above, one can explain the decoupling of environmental pressure from economic growth by its driving force, i.e., effects of technology and economic structure.

**3.3 Data preparation**

The environmental pressure indicators selected for this study were based on three criteria. Firstly, indicators were selected to cover a broad range of environmental issues such as climate change, air pollution, water quality, and waste management. Secondly, the indicators were selected in consideration to the OECD (2002) recommendations on indicators, i.e. based on policy relevance, user utility, analytical soundness, and measurability. Thirdly, indicators were selected based on the availability of data. From the above three criteria, six environmental pressure indicators were selected. These include: energy consumption (end-use), emissions of $CO_2$, $SO_2$, soot, waste water and solid waste. These indicators reflect environmental pressure from both the input and output of the socio-economic systems. Furthermore, these indicators are of significant concern to policy and decision makers and there are explicit policy targets for the reduction of energy consumption intensity, $CO_2$ emission intensity, and $SO_2$ emissions in the $12^{th}$ National Five-Year Plan of China.

For the system boundary of these indicators, in line with traditional IDA studies, we considered all industrial sectors but not the household sector (De Freitas and Kaneko, 2011; Löfgren and Muller, 2010; Pothen and Schymura, 2015). According to the Chinese Energy Statistical Yearbook and our calculations, 90% of both energy consumption and $CO_2$ emissions are from Chongqing's industrial sectors. Therefore, environmental pressures are mainly produced by the industrial sectors and the results of our study will not be significantly influenced as a result of the exclusion of the household sector from the system boundary. However, policy-makers should still be cautious that the result of our research meets a 10% error by not taking into account the household sector.

According to the statistical bureau of Chongqing, the economic system of Chongqing is divided into 41 economic sectors (see table S1 in supplementary material). To use the IDA method for analysing the driving forces of decoupling environmental pressures from economic growth in Chongqing, we need to acquire data in the 41 economic sectors, including the value added of economic output and the six environmental pressures.

The data for the value added were collected from the Chongqing Statistical Yearbooks. In order to remove the effect of inflation, we converted all current prices into 2010 constant prices using the double deflation method (Xu, 2004). Deflators were compiled according to the price indexes from the China Statistical Yearbooks and the Chongqing Statistical Yearbooks.

The detailed data sources for the six environmental pressure indicators are shown in table S2 of supplementary material. Energy consumption (end-use) is an aggregated indicator measured in units of tons of standard coal equivalent (tce), while other environmental pressure indicators are all measured in tons. The data for energy consumption are obtained from China Energy Statistical Yearbooks and Chongqing Statistical Yearbooks. The data for $CO_2$ emissions were accounted by reference to the IPCC (2006) guidelines. Due to the lack of data, we consider $CO_2$ emissions from fossil-fuel combustion, cement production, and nonferrous metal production in this study. As for $SO_2$, soot, waste water, and solid waste, the inventory data in the industrial sectors were collected from the Chongqing Statistical Yearbooks, while data in the agricultural sector, construction sector, and the service sector were estimated by Liang's method (Liang et al., 2014).

Similar to Chongqing, data for calculating decoupling indexes in other regions (including China, Beijing, Shanghai, Tianjin) were acquired and compiled from China's Energy Statistical Yearbook, China Environment Yearbook, China Statistical Yearbook, Beijing Statistical Yearbook, Shanghai Statistical Yearbook, and Tianjin Statistical Yearbook.

## 4. Results

In this section, we first show the trends of environmental pressures (as well as their uncertainties) and GDP in Chongqing from 1999 to 2010. Secondly, we show the results of the evaluation of the decoupling levels in Chongqing. Thirdly, we compare the decoupling indicators of Chongqing with those of other regions, including other Chinese municipalities, the national average and the average of OECD countries. Thirdly, we explore the driving forces for the decoupling of environmental pressures in Chongqing.

### 4.1 Trends of economic growth and environmental pressures in Chongqing during 1999-2010

Using the method introduced in section 3, we calculated the environmental pressures indicators in Chongqing during 1999-2010. As illustrated in Fig. 2a, during the period of 1999-2010, Chongqing's GDP increased by 269% and reached 793 billion CNY in 2010. The increase in GDP also resulted in environmental pressures. As illustrated in Fig. 2b, energy consumption, $CO_2$ emissions, and solid waste discharge respectively increased by 218%, 191%, and 35%, while emissions of $SO_2$, soot, and waste water respectively decreased by 22%, 35%, and 4%. These results reveal that not all environmental pressure indicators increased or increased in the same rate in tandem with the GDP growth of Chongqing.

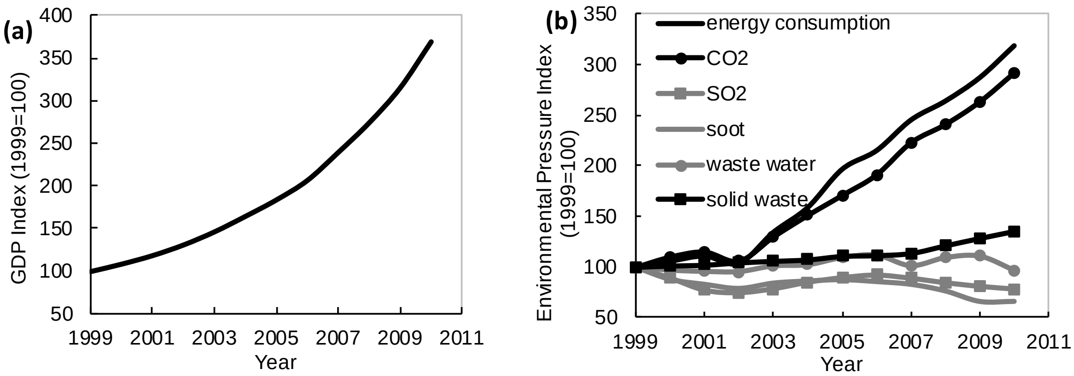


Fig. 2. Trends of GDP (a) and environmental pressure indicators (b) in Chongqing during the period 1999-2010 (All indicators are given relative to those of the year 1999, i.e., 1999 has the value 100, and indicators in other years are relative to those of 1999)

For a more refined analysis of the trends of different environmental pressure indicators, the following observations can be made: (1) Solid waste discharge increased consecutively over the period 1999-2010. (2) Energy consumption and $CO_2$ emissions fluctuated during the period 1999-2002, while after 2002 both increased rapidly. (3) Emissions of $SO_2$, soot, and waste water decreased during 1999 to 2002; after 2002, they respectively increased to their peak in the year 2006, 2005 and 2006, and gradually decreased afterwards.

Table 1. Uncertainties related to environmental pressure indicators (in %), Chongqing, 2000-2010

| | 2000 | | 2005 | | 2010 | |
|---|---|---|---|---|---|---|
| | Min. | Max. | Min. | Max. | Min. | Max. |
| $CO_2$ | -17 | 11 | -18 | 11 | -17 | 8 |
| energy consumption | 0 | 8 | 0 | 8 | 0 | 7 |
| $SO_2$ | -4 | 3 | -3 | 2 | -3 | 2 |
| soot | -4 | 6 | -4 | 6 | -6 | 8 |
| waste water | -3 | 5 | -4 | 6 | -6 | 7 |
| solid waste | -11 | 9 | -12 | 10 | -12 | 10 |

Following the method introduced by Kovanda et al. (2008), we also made an uncertainty analysis for the environmental indicators of Chongqing. In this study, the uncertainties of environmental pressure indicators mainly come from the estimation of environmental pressure data in agriculture, construction and service sectors. We estimated these data with different coefficients (e.g., $CO_2$ emission coefficients for fossil energy) and calculated the uncertainties for the overall environmental pressure indicator. The uncertainties attributed to environmental pressure indicators of Chongqing during the period 2000-2010 are summarized in table 1. Results show that the largest uncertainties are related to $CO_2$ emissions, which are up to -18% and +11% in some cases. And uncertainties are comparatively low (not exceeding -10% and +10%) for energy consumption and emissions of $CO_2$, soot and waste water.

**4.2 Decoupling indicators of Chongqing during 1999-2010**

The results of the analyses of the trends of GDP and environmental pressures in Chongqing from 1999 to 2010, reveal that GDP growth rate is higher than the growth rate of six environmental pressures. This indicates that decoupling has occurred between environmental pressures and economic growth. To put into perspective the decoupling levels with the economic development of Chongqing, we examine the level of decoupling over two periods, i.e, during the 10$^{th}$ Five-Year Plan (2000-2005) and the 11$^{th}$ Five-Year Plan (2005-2010) for National Economic and Social Development of China.

Table 2 illustrates the decoupling index of environmental pressures in Chongqing during the period of 1999-2010. From these results, it is observed that: (1) Absolute decoupling occurred for emissions of $SO_2$, soot, and waste water. Among these environmental pressures, the decoupling level for soot, DI of 0.820, is the highest, while the decoupling level of waste water is the lowest. (2) Relative decoupling occurred for energy consumption, $CO_2$ emission, and solid waste discharge. Among environmental pressures showing relative decoupling, the decoupling level of solid waste, with a DI of 0.628, is the highest; while the decoupling level for energy consumption, with a DI value of 0.123, is the lowest. (3) Among the six environmental pressures through the 1999-2010 period, soot emissions accounted for the highest decoupling level while energy consumption accounted for the lowest decoupling level.

Table 2. Decoupling index of Chongqing during different period over 1999-2010

| | 1999-2010 | 2000-2005<br>10$^{th}$ Five-Year Plan | 2005-2010<br>11$^{th}$ Five-Year plan |
|---|---|---|---|
| energy consumption | 0.123** | -0.111*** | 0.195** |
| $CO_2$ | 0.198** | 0.070** | 0.152** |
| $SO_2$ | 0.785* | 0.398** | 0.566* |
| Soot | 0.820* | 0.403* | 0.628* |
| waste water | 0.734* | 0.322** | 0.561* |
| solid waste | 0.628** | 0.345** | 0.393** |

* indicates absolute decoupling; ** indicate relative decoupling; *** indicates coupling.

The decoupling levels relative to the 10$^{th}$ and 11$^{th}$ Five-year plans, as seen in Table 2, indicates that all six environmental pressures have higher decoupling levels in the second period. Moreover, three environmental pressures reveal significant improvements in their level of decoupling. Specifically, energy consumption improved from a position of coupling (DI=-0.111) to relative decoupling (DI=0.195), while $SO_2$ and waste water discharge improved from a position of relative decoupling to absolute decoupling. Emissions of soot continued at a position of absolute decoupling in both periods, however its decoupling level slightly improved in the second period. Solid waste discharge was at a position of relative decoupling in both periods, however, its decoupling level also slightly improved in the second period. Similarly, the decoupling level of $CO_2$ emissions significantly improved from a weak position of relative decoupling, DI value of 0.07, in the first period to a stronger position of relative decoupling, DI value of 0.152, in the second period.

In terms of the uncertainties, as shown in table 3, the difference between the $CO_2$ emissions can be up to -18% by using different coefficients. However, the difference between the decoupling index for $CO_2$ emissions is relatively small (not exceeding 10%). As a result, the results of Chongqing's decoupling level for environmental pressures are reliable during the period 1999-2010.

Table 3. Comparison of $CO_2$ emissions and DI using different coefficient during different period over 1999-2010

| | 1999-2010 | 2000-2005<br>10th Five-Year Plan | 2005-2010<br>11th Five-Year plan |
|---|---|---|---|
| $CO_2$ emissions (IPCC's coefficient) (Mt) | 1002 | 375 | 661 |
| $CO_2$ emissions (Liu et al. (2015) coefficient) (Mt) | 829 | 311 | 545 |
| Difference for $CO_2$ emissions | -17% | -17% | -18% |
| DI of $CO_2$ emissions (IPCC coefficient) | 0.198** | 0.070** | 0.152** |
| DI of $CO_2$ emissions (Liu et al. (2015) coefficient) | 0.202** | 0.076** | 0.143** |
| Difference for DI of $CO_2$ emissions | 2% | 8% | -6% |

** indicate relative decoupling

### 4.3 Comparison of decoupling indicators of Chongqing with those of other regions

To compare Chongqing's decoupling level during the period 2000-2010 relative to other regions of China and OECD countries, we calculate the DI for the environmental pressure indicators for Tianjin, Shanghai and Beijing, the Chinese national average and OECD countries.

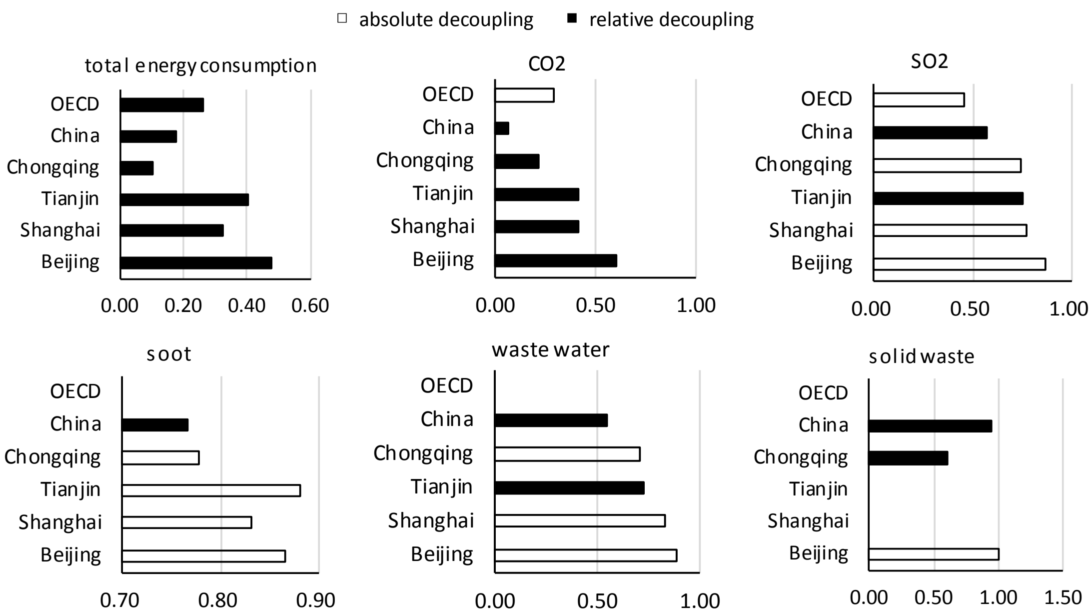


Fig. 3. Decoupling indexes for six environmental pressures in Chongqing, Tianjin, Shanghai, Beijing, the national Chinese average and OECD countries' average during 2000-2010. (Note that there is no data on soot and waste water for OECD countries, and no data on solid waste discharge in Tianjin, Shanghai and OECD countries; all data for OECD countries are acquired from http://stats.oecd.org/)

As illustrated in Fig. 3, compared with OECD countries' average, Chongqing had lower decoupling level for total energy consumption and $CO_2$ emissions, while higher decoupling level for $SO_2$ emissions. More details about the comparison of DI in Chongqing and OECD countries are shown in Fig. S1 in Supplementary Material.

Compared to the national average, Chongqing had higher decoupling levels during 2000-2010 for the six types of environmental pressures except energy consumption. However, in comparison to the other national central cities of China, the level of decoupling in Chongqing was lower than that of Beijing and Shanghai. The decoupling levels for energy consumption and solid waste discharge in Chongqing are both the lowest among the five regions, and there is a significant difference in the decoupling level of energy consumption between Chongqing and the other regions. Specifically, Chongqing's energy consumption decoupling level, i.e. DI value of 0.11, is only 60%, 33%, 26% and 22% respectively of the Chinese average national level and the cities of Shanghai, Tianjin, and Beijing. The level of decoupling of $CO_2$ emission in Chongqing while higher than the Chinese national average, is lower than the other three cities. While $SO_2$ and waste water emissions are at a position of absolute decoupling in Chongqing, their levels are less than that of the cities of Beijing and Shanghai. Finally, although the soot emissions in Chongqing are at a position of absolute decoupling and the lowest among the central national cities, their level is higher than the national Chinese average.

**4.4 Driving force for the decoupling of environmental pressure in Chongqing during 1999-2010**

The driving force, i.e., technology effect ($C_T$) and economic structural effect ($C_S$), of the decoupling of environmental pressure from economic growth in Chongqing during the period of 1999-2010 can be explained using eqs. 3-5.

As shown in Table 4, during the period 1999-2010, technological change is the dominate force contributing to the decoupling of all environmental pressures except solid waste discharge. Economic structural change however has had a very small positive effect and even negative effect to decoupling. Specifically, economic structural change had a negative effect on the decoupling of energy consumption, emissions of $CO_2$, and waste water respectively by -30.9%, -34.5% and -4.5%. As for the decoupling of emissions of $SO_2$ and soot, economic structural change had a small effect contributing respectively to 0.1% and 2.3% to their decoupling from economic growth. For solid waste, economic structure change contributed 45.1% to its decoupling, which is almost equal to the effect of technology change.

Table 4. Contributions of driving force to decoupling in Chongqing during different period over 1999-2010

| | 1999-2010 | | 2000-2005 | | 2005-2010 | |
|---|---|---|---|---|---|---|
| | $C_S$ | $C_T$ | $C_S$ | $C_T$ | $C_S$ | $C_T$ |
| energy consumption | -30.9% | 130.9% | 42.2% | 57.8% | 9.4% | 90.6% |
| $CO_2$ | -34.5% | 134.6% | -99.2% | 199.2% | 13.9% | 86.1% |
| $SO_2$ | 0.1% | 99.9% | 0.04% | 99.06% | 9.3% | 90.7% |
| soot | 2.3% | 97.7% | -0.8% | 100.8% | 11.7% | 88.3% |
| waste water | -4.5% | 104.5% | 4.0% | 96.0% | -4.0% | 104.0% |
| solid waste | 45.1% | 54.9% | 35.6% | 64.4% | 46.4% | 53.6% |

An examination of the causes of decoupling separately for the $10^{th}$ (2000-2005) and $11^{th}$ (2005-2010) five-year economic plans, as shown in Table 4, reveals interesting insights. First, our analysis reveals that similar to the total period of 1999-2010, technological change is the dominant force contributing to the decoupling of almost all environmental pressures in both the $10^{th}$ and $11^{th}$ five-year economic plans. The only exception is for the decoupling of energy consumption during the period of 2000-2005. In that period, both technological change and economic structural change negatively affected energy consumption, respectively by 42.2% and 57.5%, and resulted in the coupling of this environmental pressure with economic growth (see

Table 2). Second, our analysis of the two periods revealed that although economic structural change had small positive effects in both periods, the value of $C_s$ for all the environmental pressures, with the exception of waste water discharge, in the later period are more than the former. Therefore, the contribution of economic structural change as a driving force to decoupling reveals overall improvement. Specifically, the effect of economic structural change to the decoupling of energy consumption and emissions of $CO_2$ and soot, changed from a negative value in the period of 2000-2005 to a positive value in the period of 2005-2010. Furthermore, the positive effect of economic structure change to the decoupling of emissions of $SO_2$ and solid waste, improved respectively from 0.04% and 35.6% in the period 2000-2005 to respectively 9.3% and 46.4% in the period of 2005-2010.

## 5. Discussions

Our results indicate significant differences in the decoupling level of the environmental pressure indicators in Chongqing. Importantly, the order of the level of decoupling among the six environmental pressures is not particular to Chongqing and similar results are reported for Tianjin, Shanghai, Beijing and China (as shown in Fig. 3). Furthermore, the OECD countries echoes similar results that decoupling indexes for $CO_2$ are much lower than that of $SO_2$. These differences are mainly as a result from their driving forces, i.e., technological change and economic structural change, which are further affected by policy regulations, cost of pipe-end treatment technologies, and the co-dependence of environmental pressures. In this section, we provide a comprehensive examination on these differences.

### 5.1 Difference of decoupling level for different environmental pressures

As technological change played the dominate role for decoupling environmental pressures from economic growth in Chongqing during the period 1999-2010 (as shown in table 4), the difference of decoupling level for different environmental pressures can be explained by the difference of their technological changes.

Energy consumption had the lowest decoupling level among all environmental pressure indicators in Chongqing. This can be related to the position of the environmental pressures as either precursors or derivatives of the economic system of the urban region. As proposed by Yu et al. (2013), energy consumption is considered as a precursor input to the economic system and therefore the decoupling of energy consumption is only determined by the technology of the production process[2]. This is while pollutant emissions (e.g., emissions of $CO_2$, $SO_2$, soot, waste water and solid waste) are derivative output of the economic system and therefore the decoupling of pollutant emissions are determined by both the technology of the production process and pipe-end treatment[3]. Therefore, the decoupling level of pollutant emissions in comparison to energy consumption can be additionally improved through investments in pipe-end treatment technologies. According to the Chongqing Statistical Yearbooks, the investment in the industrial pollution treatment in Chongqing increased from 107 to 775 billion CNY during the period 1999-2010, which as a result greatly improved the technological level of

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[2] In eq. 2, $M_i/Y_i$ is energy consumption per unit of value added in economic sectors, and it is determined by the technology of the production process.

[3] In eq. 2, $M_i/Y_i$ can be further decomposed as $M_i/Y_i=(G_i/Y_i)*(M_i/G_i)$, where $G_i$ is the pollutant generation in economic sector i; $G_i/Y_i$ and $M_i/G_i$ are the pollutant generation per unit of value added and pollutant emission per unit of generation in economic sector i, which are determined by the technology of production process and pipe-end treatment, respectively.

pipe-end treatment for pollutant emissions. Therefore, energy consumption is with the lowest decoupling level among the six environmental pressures in Chongqing. As $CO_2$ is primarily produced by fossil energy, $CO_2$ generation rapidly increased with the increase of energy consumption during the 1999-2010 period. Furthermore, since no practical pipe-end treatment technology exists for $CO_2$ emissions (Zhou et al., 2010), almost all generated $CO_2$ are emitted. Therefore, the decoupling level of $CO_2$ emissions is the second lowest among the six environmental pressures in Chongqing. Importantly, the phenomenon that energy consumption and $CO_2$ emissions had the lowest decoupling level is not particular in Chongqing, and the same results are reported for Tianjin, Shanghai, Beijing, China and OECD countries (as shown in Fig. 3).

As for emissions of $SO_2$, soot, waste water and solid waste, the difference in their decoupling levels are resulting from the difference for the cost of their pipe-end treatment technologies, e.g., the fixed and operational cost for implementing pipe-end treatment facilities. With lower cost, it is much easier to implement the pipe-end treatment technology (e.g., desulfurization) and to promote the reduction of pollutant emissions, which will result in a higher decoupling level. In this vein, Zhang et al. (2008) calculated the reduction cost of soot and $SO_2$ emissions in Chinese power plants and found that it is cheaper to promote the reduction of soot than $SO_2$. Therefore, given the differences in reduction costs, we see that the decoupling level for soot is higher than that of $SO_2$. This phenomenon is not particular in Chongqing, and the same results are reported for Tianjin, Shanghai, Beijing and China (as shown in Fig. 3). As waste water and solid waste are from diversified sources, e.g., chemical plants, metallurgical plants, etc., there are many different pipe-end treatment technologies for them. Therefore, it is very hard to calculate the cost of their pipe-end treatment technologies. Hence, the difference in their decoupling level in Chongqing cannot be explained using our method. However, our results show that decoupling level for waste water emissions is lower than that of soot in Chongqing, Shanghai, Tianjin and China (as shown in Fig. 3), which indicate that the cost of pipe-end treatment technologies are higher for waste water than that for soot in these regions.

**5.2 Difference of decoupling level during different period**

A substantial improvement, as seen as in Table 2, can be noted in the decoupling levels of environmental pressures in Chongqing between the $10^{th}$ (2000-2005) and $11^{th}$ (2005-2010) economic development plans. This improvement reflects the change in policy regulations on energy and environmental issues between the two periods and more specifically mandated targets for energy consumption and pollutant emissions (GPRC, 2006). Notably, the $11^{th}$ Five Year Plan for National Economic and Social Development of China mandated the reduction of energy consumption intensity by 20% and major pollutant emissions, including $SO_2$ emissions, to be reduced by 10%. To achieve these targets, the local Chongqing government had adopted a set of measures, such as implementing the regulations of industrial structure adjustment and cleaner production set by the central government of China. As a result, significant investments were made on upgrading traditional manufacturing processes and eliminating out-dated technologies (Yu et al., 2015). These investments significantly contributed to improvements in the driving force of decoupling especially for technological change, whereby the energy intensity of major energy-extensive industrial sectors had been significantly reduced. According to data from the Chongqing Statistical Yearbooks, energy intensity in the petroleum processing, chemical products, non-metal mineral products, ferrous metal smelting and processing, non-ferrous metal smelting and processing, and power production sectors were respectively reduced by 63%, 41%, 30%, 37%, 51% and 40%.

### 5.3 Promoting further decoupling for all environmental pressures

Technological and economic structural change are two driving forces of decoupling environmental pressures from economic growth. As shown in Table 4, technological change played the dominate role for promoting decoupling for almost all environmental pressures during the period 1999-2000. During this period, technological advancement was achieved mainly as a results of investments in line with cleaner production practices as mandated by the Chinese government. Technological advancement should remain as cornerstone of future policy on increasing the decoupling of environmental pressures from economic growth. However, decoupling levels can be further increased through technological advancement by integrating targeted mandates with policies aimed at giving incentives to firms, e.g. financial subsidies and tax rebates.

In comparison to technological change, economic structure change played a relatively small role for decoupling during the 2000-2010 period. In general, the promotion of decoupling through the shifting economic structure is not straightforward and may lead to both positive and negative contributions to environmental pressures. As shown in Table 4, economic structure change negatively affected the decoupling of energy consumption and emissions of $CO_2$ and soot, while positively affecting the decoupling of emissions of $SO_2$, waste water, and solid waste during the period 2000-2005. After implementing activities of industrial structure adjustment, economic structure finally moved into the direction of decoupling almost all the six environmental pressures. However, its contribution for decoupling of waste water discharge turned from a positive value to a negative value during this period. This implies that promoting the decoupling of a particular environmental pressure through economic structure change may have benefits or trade-offs with other environmental pressures (Liang et al, 2013a). Therefore, policy-makers should take caution in shifting or changing economic structure and consider the complex effects of decoupling environmental pressures through such policies. Specifically, we suggest policy-makers to conduct integrated policy modelling (Liang et al., 2013a) to elaborate the best set of schemes for the decoupling of a wide range environmental pressure indicators. In this avenue, we suggest the use and advancement of integrated policy modelling tools, e.g. the MARKAL model (Fishbone and Abilock, 1981) and the GAINS model (Tohka, 2005). For example, Gielen and Changhong (2001) used the MARKAL model to elaborate the optimal set of policies for reducing $SO_2$, NOx, and $CO_2$ in Shanghai.

### 5.4 Recommendations for other regions and future studies

As the typical representation of a Chinese megacity, Chongqing has experienced rapid economic development during its industrialization and urbanization processes during the period 1999-2010. The analysis of the decoupling of environmental pressures from economic growth in Chongqing can provide important lessons for other regions, especially for those undergoing rapid economic development and socioeconomic transition. For example, many regions are shifting their economic structures to pursue green economy agendas. However, they should be aware that these changes to economic structures will have both negative and positive effects for the decoupling of different environmental pressure. To avoid negative effects, policy-makers should take into consideration the potential effects of economic structure change to decoupling through the use of integrated policy modelling.

We suggest the following two avenues for future research in this area. First, the issue of uncertainties on the quality of urban data can be improved through Monte Carlo simulations. These simulations can be useful in estimating the margins of uncertainty for environmental pressure indicators in the agricultural, construction, and the service sectors. Second, the IDA method used in this research explains the dynamics of environmental pressure indicators from the production perspective and not from the consumption perspective. For future research, we suggest further exploration of the driving forces of decoupling from the consumption perspective. In this avenue, methods from structural decomposition analysis can be of great use.

## 6. Conclusions

This paper presents Chongqing as a case study to explore the decoupling of environmental pressure from a rapid urban economic development. Our results indicate that absolute decoupling occurred for emissions of $SO_2$, soot, and waste water, while relative decoupling occurred for energy consumption, emissions of $CO_2$, and solid waste during the period 1999-2010. During this period, the decoupling level of Chongqing was above the Chinese national average while below those of Beijing and Shanghai. Our results indicate that technological change had the highest contribution for inducing decoupling for all environmental pressures while economic structural change had both a positive and negative contribution. For further decoupling, we suggest government mandated environmental targets to be integrated with financial incentives, e.g., financial subsidies and tax rebates, to better promote the effects of technology advancement by firms. For further decoupling through shifting the economic structure, we suggest policy-makers to conduct integrated policy modelling to elaborate the best set of schemes.

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## References

Andreoni, V., Galmarini, S., 2012. Decoupling economic growth from carbon dioxide emissions: A decomposition analysis of Italian energy consumption. Energy 44(1), 682-691.

Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.O., Levin, S., Maler, K.G., Perrings, C., Pimentel, D., 1995. Economic growth, carrying capacity, and the environment. Science 268, 520-521.

Conrad, E., Cassar, L. F., 2014. Decoupling Economic Growth and Environmental Degradation: Reviewing Progress to Date in the Small Island State of Malta. Sustainability 6(10), 6729-6750.

De Freitas, L.C., Kaneko, S., 2011. Decomposing the decoupling of CO2 emissions and economic growth in Brazil. Ecol. Econ. 70(8), 1459-1469.

European Commission, 2005. Thematic Strategy on the Sustainable Use of Natural Resources. COM(2005) 670 Final. European Commission, Brussels.

Fishbone, L.G., Abilock, H., 1981. Markal, a linear-programming model for energy systems analysis: Technical description of the bnl version. Int. J. of Energ. Res. 5(4), 353-375.

GC - Government of Chongqing, 2011. 11th Five-Year Plan for National Economic and Social Development of Chongqing. http://www.cqdpc.gov.cn/article-1-16763.aspx

Gielen, D., Changhong, C., 2001. The CO2 emission reduction benefits of Chinese energy policies and environmental policies: A case study for Shanghai, period 1995–2020. Ecol. Econ. 39, 257-270.

GPRC - Government of the People's Republic of China, 2006. 11th Five-Year Plan for National Economic and Social Development of China. http://www.gov.cn/gongbao/content/2006/content_268766.htm.

Grimm, N.B., 2008. Global change and the ecology of cities. Science 319, 756–760.

Holdren, J.P., 2008. Science and technology for sustainable well-being. Science 319, 424-434.

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html.

Kovanda, J., Hak, T., 2007. What are the possibilities for graphical presentation of decoupling? An example of economy-wide material flow indicators in the Czech Republic. Ecol. Indic. 7(1), 123-132.

Kovanda, J., Hak, T., Janacek, J., 2008. Economy-wide material flow indicators in the Czech Republic: trends, decoupling analysis and uncertainties. Int. J. Environment and Pollution 35(1), 25-41.

Liang, S., Liu, Z., Crawford-Brown, D., Wang, Y., Xu, M., 2014. Decoupling analysis and socioeconomic drivers of environmental pressure in China. Environ. Sci. Technol. 48(2), 1103-1113.

Liang, S., Xu, M., Suh, S., Tan, R.R., 2013a. Unintended environmental consequences and co-benefits of economic restructuring. Environ. Sci. Technol. 47(22), 12894-12902.

Liang, S., Xu, M., Zhang, T., 2012. Unintended consequences of bioethanol feedstock choice in China. Bioresour. Technol. 125, 312-317.

Liang, S., Xu, M., Zhang, T., 2013b. Life cycle assessment of biodiesel production in China. Bioresour. Technol. 129, 72-77.

Liu, N., Ang, B.W., 2007. Factors shaping aggregate energy intensity trend for industry: Energy intensity versus product mix. Energ. Econ. 29(4), 609-635.

Liu, Z., Guan, D., Wei, W., Davis, S. J., Ciais, P., Bai, J., Peng, S., Zhang, Q., Hubacek, K., Marland, G., Andres, R. J., Crawford-Brown, D., Lin, J., Zhao, H., Hong, C., Boden, T. A., Feng, K., Peters, G. P., Xi, F., Liu, J., Li, Y., Zhao, Y., Zeng, N., He K., 2015. Reduced carbon emission estimates from fossil fuel combustion and cement production in china. Nature 524(7565), 335-338.

Löfgren, Å., Muller, A., 2010. Swedish CO2 emissions 1993–2006: an application of decomposition analysis and some methodological insights. Environ. Resour. Econ. 47(2), 221-239.

Lu, I.J., Lin, S.J., Lewis, C., 2007. Decomposition and decoupling effects of carbon dioxide emission from highway transportation in Taiwan, Germany, Japan and South Korea. Energ. Policy 35(6), 3226-3235.

Lu, Z., Wang, H., Yue, Q., 2014. Decoupling Analysis of the Environmental Mountain—with Case Studies from China. J. Ind. Ecol. DOI: 10.1111/jiec.12226

Mazzanti, M., Zoboli, R., 2008. Waste generation, waste disposal and policy effectiveness: Evidence on decoupling from the European Union. Resour. Conserv. Recy. 52(10), 1221-1234.

OECD – Organization for Economic Co-operation and Development, 2002. Indicators to Measure Decoupling of Environmental Pressure from Economic Growth. Sustainable Development. http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=sg/sd(2002)1/final.

Okadera, T., Watanabe, M., Xu, K., 2006. Analysis of water demand and water pollutant discharge using a regional input–output table: an application to the City of Chongqing, upstream of the Three Gorges Dam in China. Ecol. Econ. 58, 221–237.

Pothen, F., Schymura, M., 2015. Bigger cakes with fewer ingredients? A comparison of material use of the world economy. Ecol. Econ. 109, 109-121.

Ren, S., Hu, Z., 2012. Effects of decoupling of carbon dioxide emission by Chinese nonferrous metals industry. Energ. Policy 43, 407-414.

Satterthwaite, D., 2008. Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. Environment and urbanization 20(2), 539-549.

Sjöström, M., Östblom, G., 2010. Decoupling waste generation from economic growth—A CGE analysis of the Swedish case. Ecol. Econ. 69(7), 1545-1552.

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energ. Econ. 34(1), 177-188.

Tachibana, J., Hirota, K., Goto, N., Fujie, K., 2008. A method for regional-scale material flow and decoupling analysis: A demonstration case study of Aichi prefecture, Japan. Resour. Conserv. Recy. 52(12), 1382–1390.

Tang, Z., Shang, J., Shi, C., Liu, Z., Bi, K., 2014. Decoupling indicators of CO2 emissions from the tourism industry in China: 1990-2012. Ecol. Indic. 46, 390-397.

Tapio, P., 2005. Towards a theory of decoupling: degrees of decoupling in the EU and the case of road traffic in Finland between 1970 and 2001. Transport Policy 12(2), 137-151.

Tohka, A., 2005. The GAINS model for greenhouse gases–version 1.0. IIASA Interim Report IR-05-056, IIASA, Laxenburg.

UN - United Nations, 2008. World Urbanization Prospects: The 2007 Revision. http://www.un.org/esa/population/publications/wup2007/2007WUP_ExecSum_web.pdf

UNEP – United Nations Environment Programme, 2011. Decoupling natural resource use and environmental impacts from economic growth. http://www.unep.org/resourcepanel/decoupling/files/pdf/Decoupling_Report_English.pdf.

Van Caneghem, J., Block, C., Van Hooste, H., Vandecasteele, C., 2010. Eco-efficiency trends of the Flemish industry: decoupling of environmental impact from economic growth. J. Clean. Prod. 18(14), 1349-1357.

Van der Voet, E., Van Oers, L., Moll, S., Schütz, H., Bringezu, S., De Bruyn, S., Sevenster, M., Warringa, G., 2005. Policy Review on Decoupling: Development of indicators to assess decoupling of economic development and environmental pressure in the EU-25 and AC-3 countries. EU Commission, DG Environment, Brussels.

Wang, H., Hashimoto, S., Yue, Q., Moriguchi, Y., Lu, Z., 2013. Decoupling analysis of four selected countries. J. Ind. Ecol. 17(4), 618-629.

Wiedmann, T.O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., Kanemoto, K., 2015. The material footprint of nations. Proc. Natl. Acad. Sci. U. S. A. 112, 6271-6276.

Xu, X., 2004. China National Economy Accounts. China Statistics Press, Beijing.

Xue, J., 2012. Limits to decoupling strategies for sustainable housing development: the Hangzhou experience. J. Environ. Plann. Man. 55(8), 1004-1021.

Yang, Y., Bae, J., Kim, J., Suh, S., 2012. Replacing gasoline with corn ethanol results in significant environmental problem-shifting. Environ. Sci. Technol. 46(7), 3671-3678.

Yu, Y., Chen, D., Zhu, B., Hu, S., 2013. Eco-efficiency trends in China, 1978-2010: decoupling environmental pressure from economic growth. Ecol. Indic. 24, 177–184.

Yu, Y., Ren, H., Kharrazi, A., Ma, T., Zhu, B., 2015. Exploring socioeconomic drivers of environmental pressure on the city level: The case study of Chongqing in China. Ecol. Econ. 118, 123-131.

Zhang, F., Xu, L., Liu, G., 2008. Estimation and management of environmental cost of power plants. Engineering Journal of Wuhan University 41, 99-102. (in Chinese)

Zhang, L., Xue, B., Geng, Y., Ren, W., Lu, C., 2014. Emergy-based city's sustainability and decoupling assessment: Indicators, features and findings. Sustainability 6(2), 952-966.

Zhou, W., Zhu, B., Fuss, S., Szolgayova, J., Obersteiner, M., Fei, W., 2010. Uncertainty modeling of CCS investment strategy in China's power sector. Appl. Energ. 87(7), 2392-2400.

Zhu, H., Li, W., Yu, J., Sun, W., Yao, X., 2013. An analysis of decoupling relationships of water uses and economic development in the two provinces of Yunnan and Guizhou during the first ten years of implementing the Great Western Development Strategy. Procedia Environmental Sciences 18, 864-870.