Environmental Pollution 249 (2019) 676–685

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Loss accounting of environmental pollution within Pearl River Delta region, South China

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A R T I C L E I N F O

Article history:
Received 10 September 2018
Received in revised form
7 March 2019
Accepted 19 March 2019
Available online 24 March 2019

Keywords:
Pearl River delta
Loss accounting
Environmental degradation cost
Environmental degradation index

A B S T R A C T

Economic development puts pressure on environment through air, water and land degradation, which in turn brings real costs to the economy. Actual economy growth should therefore consider the environmental degradation cost resulted from economic activities. Pearl River Delta (PRD) region as a typical delta area with rapid development in China, is with great significance to understand the loses resulted from environmental pollution.

This study conducts an environmental economic accounting within the PRD region from 2011 to 2015 using the environmental degradation cost accounting approach. We identified and calculated the economic, agricultural, industrial and social losses resulting from air, water and waste pollution with different valuation methods, which includes shadow price, replacement costs, market value method, etc. The results showed the total environmental degradation cost ranged from 18.1 to 19.8 billion US$ and the environmental degradation index declined slightly over the years, with significant differences among cities.

It implied that the environmental condition of PRD region has been continuously improved over the years, but the capacity of environment control between cities had large differences. Cities in PRD region should therefore take measures tailored to their current situation to optimize their resource endowment and industrial structure, to overcome the conflicts between economic development and environmental protection. For cities with relatively high degradation cost, it is urgent to accelerate the efforts in improving the quality of the environment and ecosystem. For cities with lower degradation cost, it is important to take actions to keep on a sustainable and ecological efficient developing path.

Main findings: The total environmental degradation cost of the PRD region is firstly calculated with insights on environmental management.

1. Introduction

Since traditional gross domestic product (GDP) accounting could not reflect total social cost of economic growth, the integration of human activities-induced consumption and pollution of natural resources into the macro-economic accounting has been a heated topic in the field of environmental economics (Costanza et al., 1997). Norway, the Netherlands, Germany, Poland and the United States are among the first countries who attempted to incorporate natural capitals into national economic accounting frameworks (Wang, 2016). Norway launched the research on green accountings in the early 1970s and developed its own methods in response to the ever-increasing environmental pressure (Zi, 2006). Germany started its research on environmental accountings in the 1990s. Many of the environmental indicators were embedded into the expanded national accounting system since then (Shi and Liang, 2004). It also led the research on material flow accounting and land accounting (Hecht, 2000). In 1993, the United Nations published the "*System for Integrated Environmental and Economic Accounting* (SEEA)", where the concept of 'green GDP' was firstly proposed, to

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https://doi.org/10.1016/j.envpol.2019.03.081
0269-7491/

systematically correct conventional GDP by considering natural goods and services that are otherwise neglected (Gao, 2015). Various indicator systems have then been built to meet practical needs. Indicators with consideration of environmental cost, such as Genuine Saving Rate (GSR) (Hamilton, 2010), Ecological Footprint (EF) (Wackernagel, 1996), and Sustainable Development Indicators (SDI) (Mederly et al., 2003), were also used to characterize the sustainability of ecological environment. These efforts highlighted the importance of measuring costs of natural resources depletion and environmental degradation and encouraged many studies on estimating the costs of natural degradation of specific pollution, industries or ecosystems (Sutton and Costanza, 2002; Reddy, 2003; Bolt, Ruta and Sarraf, 2005; Xiao and Mao, 2006; Jia et al., 2012; United Nations, 2012; Fadi, Sherif and Ilyes, 2014). In 2000, the World Bank launched a systematic program to measure the cost of environmental degradation in several nations of the Middle East and North Africa region (Croitoru and Sarraf, 2010). These practices not only raised the world's awareness on the real costs of environmental damage, but also developed standard valuation techniques to measure the cost of environmental loss.

Along with the rapid economic growth in China, the dilemma between economic development and environmental protection has become a major issue, which leads to a growing interest on green accountings. Since the first research on green GDP system been published in 1990, several frameworks for relevant accounting have been established in China (Lei, 1999; RGSDIS, 1999). It was however not until 2006 that the first report concerning China's green national economic accounting, the so called “green GDP 1.0” was published (Yu et al., 2009; Wang et al., 2006). Due to the limitations regarding data availability and accounting methods, this “green GDP 1.0” only calculated part of the loss caused by environmental pollution. In 2015, the “green GDP 2.0”, a more comprehensive and creative accounting framework was launched to tackle the problems.

Currently, the “green GDP 2.0” accounting system is still in its preliminary stage of application and it is urgent to accelerate pilot studies on provincial and municipal levels. PRD region was chosen to be one of the pilot areas by the central government considering its leading role as a reform test filed in China. The importance of the PRD region is rapidly increasing in recent years as it became the core part of the Guangdong-Hong Kong-Macau Bay Area, a strategic development area proposed by the Chinese government in 2016, to be built as a world-leading metropolitan region. This plan brings explosive growth in the PRD region. In 2017, the PRD region contributed 84.3% of Guangdong's GDP and 9.23% of China's GDP with only 0.57% of the national territory area (GDSTATS, 2018). The rapid and intensive development in the region inevitably brings great challenges on the environment. Industrial production discharges pollutants into the air and waterways, threatening the public health. Unsustainable agricultural practices bring irreversible damage to the land. Ever-increasing municipal waste increases the waste treatment costs and puts great pressure on landfill. Yet the real costs resulted from these and other forms of environmental degradation often go unmeasured, and thus, the real costs remain largely unknown, which limits the governments' ability to take effective actions to reduce or reverse the degradation. It is therefore necessary to estimate the costs of environmental loss in the region to provide policy makers a broader picture on the actual cost of economic development and to develop well-considered regional development plans.

This study aimed to extend the pilot study and to conduct an environmental loss accounting in PRD region. With the quantitative assessment for the loss caused by environmental pollution, the study examined the environmental prices that had been paid from 2011 to 2015. This study provides a methodology made specific to the PRD region to estimate the environmental loss and the implications for the region. There are several reasons of choosing the PRD region as the research area: (1) A national accounting research program assigned by the central government chose the PRD region as a pilot study area and have been conducting the Green GDP 2.0 accounting research in the region, which helped to establish standard methods for collecting relevant data required by our research, and also in a way ensure there is adequate data needed to calculate the loss. (2) The national research program also provided us with better and clearer understanding of the environmental issues and ecosystem services within the region. (3) There has been explosive growth in the region in recent decades and it is of crucial importance to understand how this rapid economic growth has affected the environment and what the true costs of the development would be if the loss resulted from the environmental degradation is considered. The research would serve as a powerful and essential tool to inform better, well-considered policy decisions regarding trade-offs involved in balancing economic development and environmental protection. (4) The PRD region has always played a leading role as a reform test filed in China, which indicates its function as a demonstration and model for other regions and cities in China. Furthermore, its importance is rapidly increasing in recent years as it became the core part of the Guangdong-Hong Kong-Macau Bay Area. Being a typical urban environment with rapid growth, the results of this study in PRD could be used as an important indicator for monitoring regional sustainable development and would provide valuable insights to new industrializing regions not only in China, but also other urban regions undergoing rapid economic growth around the globe.

2. Materials and methods

2.1. Study area

The PRD region, located at the central-south of Guangdong Province, consists of the nine cities, namely Guangzhou, Shenzhen, Zhuhai, Foshan, Zhaoqing, Zhongshan, Jiangmen, Huizhou and Dongguan (Fig. 1), of which Guangzhou and Shenzhen have higher status in the governmental hierarchy (Wang et al., 2017). In 2016, the Chinese government announced the strategic plan of developing the Guangdong-Hong Kong-Macau Bay Area, bringing new development highlights to PRD. As one of the regions with the highest economic developing level and the strongest economic performance in China, PRD region is currently playing a leading role in social and economic development and ecological environmental governance in China. In 2017, the regional GDP of PRD accounted for over 84% (GDSTATS, 2018) of Guangdong Province's GDP, and its per capita GDP exceeded the average level of moderately developed countries. The urbanization rate, reaching over 84% (GDSTATS, 2018), also meets the criteria of mature stage. Furthermore, the efficiency of resource utilization in PRD region has been remarkably increased and achieved the advanced level in recent years in China.

Regarding environmental quality, regional water and air quality are both at the first-class level in China. The Pearl River water quality currently ranks the first among the seven major national water systems. The atmospheric quality in PRD is also the best compared to the other two key urban regions in China, namely the Yangtze River Delta and Beijing-Tianjin-Hebei Regions. Several cities in PRD region such as Shenzhen, Huizhou, Zhuhai and Zhongshan remain to be the top cities of national key cities in the air quality ranking. It can be thus seen that the coordinated development between economy and environment has emerged in PRD region.

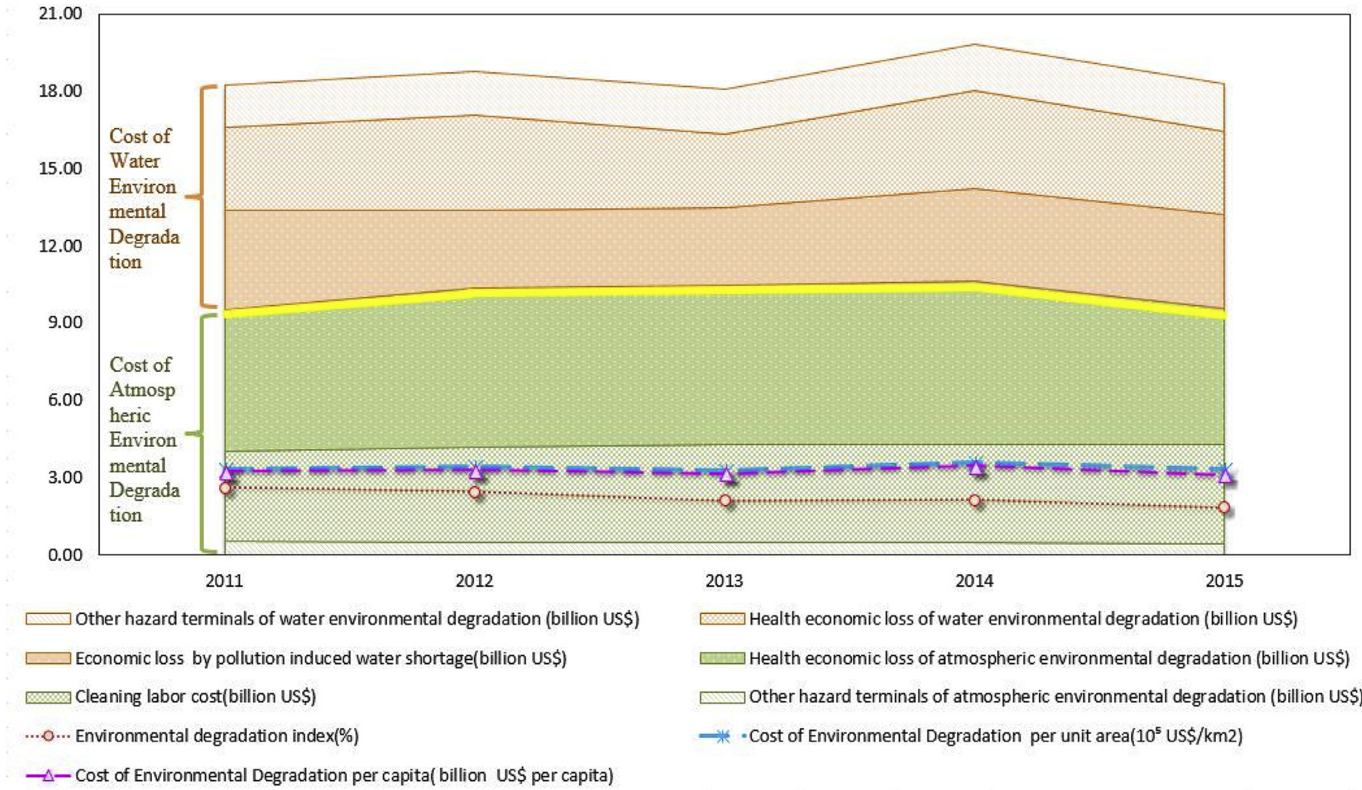

Fig. 1. Environmental degradation cost (including per unit land area and per capita costs) and its structural analysis (atmospheric and water environmental degradations), as well as environmental degradation index within PRD area from 2011 to 2015, with changes of major hazard terminals of water and atmospheric environment, such as health economic loss, economic loss caused by pollution induced water shortage and cleaning labor cost.

2.2. Accounting method

The objective of the environment loss accounting is to estimate the cost of environmental degradation at the regional level. The valuation covers impacts on three environmental categories:

Water: loss resulted from water degradation, such as economic loss led by pollution induced water shortage, agricultural yield loss resulted from polluted water, additional costs paid for polluted water treatment as well as health loss caused by water contamination.

Air: loss resulted from atmospheric degradation, such as crop reduction caused by air pollution, material corrosion resulted by air pollution and extra cleaning costs caused by air pollution.

Solid waste: loss resulted from inappropriate collection, transport and treatment of solid waste.

In general, there are two different approaches of accounting environmental loss, pollution restoration cost method and environmental degradation cost accounting (PRCEE et al., 2006). The first method attempts to understand the value of environment through the cost of recovering the environmental benefits lost to degradation. The accounting of environmental degradation cost on the other hand, focuses on the negative impacts of pollution emission or discharge, quantifying the impacts from macrocosm, such as the impacts on product output, human health, and ecological environment.

Relatively, the latter, environmental degradation cost is more appropriate for this study as it focuses on the damage and therefore provide a more comprehensive perspective on environmental loss. Through calculating the cost we have to pay for the environmental damage, the actual price of economic development, the social and environmental risks could be better understood.

The accounting methods of environmental degradation cost tailored to the PRD region is provided in Table 1. In this framework, total environmental degradation cost (TEC) is calculated based on three environmental categories, water pollution, air pollution and waste pollution. These dimensions of costs, encompassing the major environmental concerns in the PRD region, could be operationalized through identifying and calculating the economic, agricultural, industrial and social losses resulting from the related pollution media, with considerations on the main environmental concerns in the PRD region, the availability of relevant data, as well as the available valuation methods. To be specific, water environmental degradation cost (WC) is calculated by the costs on pollution induced water shortage, agricultural loss, industrial water treatment, city life quality degradation as well as health issues resulted from polluted water or water shortage. Atmospheric environmental degradation cost (AC) is operationalized through health loss, agricultural loss, material loss and cleaning labor cost generating from air pollution. Lack of data on waste limits the possibility of accounting the overall degradation cost of solid waste (SWC) in PRD region. Our framework therefore focuses on the accounting of agricultural economic losses caused by land occupation of solid waste instead. The actual environmental degradation cost resulted from waste pollution would therefore be much greater than our estimation.

For each of the three environmental categories mentioned above, the study calculates the impacts of environmental degradation with different assessment methods. Table 1 provides a summary of these methods, while the following formula briefly describe the accounting method:

$$TEC = WC + AC + SWC$$

Table 1
The accounting methodology of environmental degradation cost within PRD area.

Pollution Media	Pollution Hazard Terminal	Accounting Formula	Assessment Method
Water environmental degradation costs	Economic loss by pollution induced water shortage	$EC_p = Q_{lp} \cdot P_s$ In the formula, EC_p is the economic loss by pollution induced water shortage, Q_{lp} is the pollution induced water deficit, P_s is the shadow price of water resource (Jing and Chen, 2005).	Statistical analysis, Shadow price method
	Agricultural economic loss	$EC_c = Q_{ce} \cdot P_c$ In the formula, EC_c is the agricultural economic loss by water pollution, Q_{ce} is the agricultural water consumption with worse than Grade V water quality, P_c is the shadow price of water for agricultural use.	Statistical analysis, Remote sensing image, Shadow price method
	Additional cost of industrial water treatment	$EC_i = Q_{ie} \cdot P_i$ In the formula, EC_i is the additional cost of industrial water treatment caused by water pollution, Q_{ie} is the industrial water consumption with worse than Grade IV water quality, P_i is the average additional cost of industrial water treatment.	Statistical analysis, Replacement cost (cost of pollution treatment)
	Economic loss by city life	$EC_h = EC_{h1} + EC_{h2} = Q_{he} \cdot P_h + \sum_{j=1}^{3} P_j \cdot H \cdot C_j \cdot \alpha$ In the formula, EC_h is the economic loss by city life influenced by water pollution, and the loss includes two aspects, the additional cost of water treatment needed from water plants (EC_{h1}) and the replacement cost of clean water used in families (EC_{h2}); Q_{he} is the supply quantity of drinking water quality that worse than Grade III; P_h is the average additional cost of domestic water treatment; P_j is the annual average cost of three substitutions for household clean water use including barrelled water, purifying water dispensers and water filtration units; H is the total number of households in city; C_j is the percentage of the three substitutions selected by city households; α is the percentage of households using replaced clean water by considering health and hygiene matters.	Statistical analysis, Market value method (Peng, 2007)
	Healthy economic loss	$EC_w = EC_{w1} + EC_{w2} = \sum_{i=1}^{9} P_{vi} \times r_i \times c_i + P_{edw} \cdot \sum_{i=1}^{t} GDP_{vi}$ In the formula, EC_w is the healthy economic loss caused by water pollution, and the loss includes two types, one caused by waterborne infectious diseases (EC_{w1}) and another caused by the death of malignant tumor (EC_{w2}); P_{vi} is the rural population in PRD area; r_i is the rural tap water rate in each city; c_i is the per capita profit for improving drinking water quality in each city; P_{edw} is the number of premature deaths from malignant tumor caused by current situation of water pollution, and it adopts the relative risk estimation of malignant tumor caused by drinking water pollution (Koivusalo et al., 1994; Sandor et al., 2001; Yu and Lu, 2005); GDP_{vi} is the rural per capita GDP in year i; t is the average life loss years due to the premature deaths from malignant tumor caused by water pollution.	Statistical analysis, Human capital method
Atmospheric environmental degradation costs	Healthy economic loss	$EC_a = EC_{a1} + EC_{a2} + EC_{a3} = P_{eda} \cdot \sum_{i=1}^{t1} GDP_{ci} + P_{eh} \cdot (C_h + WD \cdot C_{wd}) + \gamma \cdot P_{eda} \cdot \sum_{i=1}^{t2} GDP_{ci}$ In the formula, EC_a is the healthy economic loss caused by air pollution, and the loss includes three aspects, pollution-related premature deaths (EC_{a1}), hospitalization (EC_{a2}) and the disablement caused by chronic bronchitis (EC_{a3}); P_{eda} is the number of premature deaths caused by current situation of air pollution, and it adopts the relative risk estimation of health terminal by air pollution (Ostro and Rothschild, 1989; Ostro, 1990; Ostro et al., 1991; Ostro, 2004); GDP_{ci} is the urban per capita GDP in year i; $t1$ is the average life loss years of all-cause mortality induced by air pollution; P_{eh} is the number of inpatients with air pollution related diseases; C_h is the cost of hospitalization; WD is the number of sick days; C_{wd} is the cost of sick leave; γ is the loss coefficient of disablement caused by chronic bronchitis; $t2$ is the average life loss years by chronic bronchitis.	Statistical analysis (Wang et al., 2005)、Exposure-response functions for related diseases (Aunan and Pan, 2004)、Human capital method (Han, 2006)
	Agricultural economic loss	$C_{ac} = \sum_{i=1}^{n} P_{ai} \cdot Q_{ai}$ In the formula, C_{ac} is the economic loss from crop reduction caused by air pollution; P_{ai} is the market price of crop i; Q_{ai} is the per unit yield of the polluted urban crop i, and it is estimated by dose-response relation.	Statistical analysis, Exposure-response functions for agricultural products (Zhang et al., 1998), Market value method
	Material economic loss	$EC_m = \sum_{i=1}^{n} C_{mi} = \sum_{i=1}^{n} (1/L_{pi} - 1/L_{0i}) \cdot C_{0i}$ In the formula, EC_m is the economic loss from material corrosion caused by air pollution; C_{mi} is the economic loss of building material i caused by acid rain and SO_2; L_{pi} is the material life of i under polluted environment; L_{0i} is the product life of building material i under clean environment; C_{0i} is the one-time expense of repair or replacement for building material i.	Statistical analysis, Remote sensing image, Exposure-response functions for building materials (Maeda et al., 2000; He, 2000: Li, 2007), Market value method
	Cleaning labor cost	$C_c = C_h + C_s = H \cdot GDP_c \cdot (\beta - \beta_0) + \sum_{i=1}^{4} \Delta C_{si} \cdot Q_{si}$ In the formula, C_c is the cost of cleaning labor caused by air	

(continued on next page)

Table 1 (*continued*)

Pollution Media	Pollution Hazard Terminal	Accounting Formula	Assessment Method
		pollution, and it includes the increasing cleaning fee from both households (C_h) and society (C_s); H is the number of households in cities; GDP_c is the per capita GDP of cities; β and β_0 are the coefficients of cleaning cost for a polluted city and a cleaning city, respectively; ΔC_{si} is the average additional cost of cleaning labor for each bus and tax, unit road and building area in a polluted city; Q_{si} is the number of exposed stock of city buses, taxes, roads and buildings in a polluted city.	Statistical analysis, Remote sensing image, Coefficient method of cleaning cost (Holubka et al., 2000; Schmitz et al., 2000), Market value method
Environmental degradation costs by solid waste		$L = \sum_{i=1}^{n} E_i \cdot S_i$ In the formula, L is the economic loss caused by the occupation of land by solid waste; E_i is the economic value coefficient of crop product each year by land type i; S_i is the occupation area of land type i by storage and discharge of solid waste.	Statistical analysis, Opportunity cost approach

$$WC = (EC_p + EC_c + EC_i + EC_h + EC_w)$$

$$AC = (EC_a + C_{ac} + EC_m + C_c)$$

$$SWC = L$$

$$TEC = (EC_p + EC_c + EC_i + EC_h + EC_w) + (EC_a + C_{ac} + EC_m + C_c) + L$$

EC_p: economic loss resulted from pollution induced water shortage; EC_c: agricultural yield loss by water pollution; EC_i: additional cost of industrial water treatment; EC_h: economic loss by city life influenced by water pollution; EC_w: health loss caused by water pollution (waterborne infectious diseases or related death); EC_a: health loss caused by air pollution; C_{ac}: economic loss from crop reduction caused by air pollution; EC_m: economic loss from material corrosion caused by air pollution; C_c: additional cost of cleaning labor caused by air pollution; L: economic loss caused by the land occupation of solid waste.

2.3. Data

Considering the availability of data and the comparability in time serial, the data on environmental quality of various cities within PRD region during 2011–2015 was selected to perform the accounting. The data used in the paper were derived from the a number of existing databases including: statistical yearbook and communiqué of Guangdong Province (GDSTATS, 2011–2016, GDEP, 2011–2016; GDRC, 2011–2015), National Meteorological Science Data Sharing Service Platform (CMA, 2011–2015), Chinese Health Statistics Yearbook (NHFPC of PRC, 2011–2015), Resource and Environmental Data Cloud Platform (IGSNRR, 2011–2015), China Soil Database (ISS, 2011–2015), as well as results based on related technical guidance, dose-response function (ECON, 2000; Xia, 1998). Data of remote sensing for calculation come from MODIS data, which were preliminarily processed by the Institute of Geographic Sciences and Natural Resources Research with spatial resolution of 30 m*30 m. Annual value assessment parameters were used as economic loss assessment parameters after adjustment by urban price indexes.

2.4. Uncertainty analysis

Our attempt to calculate the environmental degradation loss in the PRD region is limited for several reasons, including:

(1) Although we have attempted to calculate the total loss, our research leaves out many categories of environmental degradations, which have not yet been adequately studied within the region due to limitations in data availability and reliability, such as land degradation, deforestation, and losses of fisheries. This highlights the need for further research on the regional ecosystem services. With more data and studies becoming available, we expect the total loss to increase.
(2) It should also be noted that, there are still several controversial issues regarding the accounting method, especially considering the complexity of impacts of environmental pollution as well as the difficulty of data collection. Certain environmental pollution, such as clearing forests, discharging pollutants into water, poisoned soil might lead to apparent, instant environmental loss. In most cases, however, the impacts of environmental pollution are hidden and far-reaching, making it difficult to calculate the actual cost of such degradation. The valuation methods, such as direct market cost, shadow price, travel costs, etc., only provide an estimation which might be a huge underestimation. This method is thus a conservative one, which requires further improvement in the future studies.
(3) Furthermore, the results calculated for a given environmental degradation depends largely on the choice of valuation method, which represents different economic and environmental context. In other words, the results might differ greatly if different methods were used (De Groot et al., 2012).
(4) Our calculation is based on a static model where we have assumed that the degradation of the environment and ecosystems is independent to each other. This in fact ignores the complex, dynamic and inter-dependent relationships among environmental categories. The estimates could therefore change drastically as more research on dynamic environmental models become available. This signals the next step in deriving more accurate estimates of the environmental degradation cost.

Despite all these uncertainties mentioned above, we still hold the belief that it is important to understand the economic loss due to environmental degradation, if only to establish a rough, initial estimation, which, because of the limitations, might only represents a minimum value for environmental loss.

3. Results

3.1. Environmental degradation cost accounting

For PRD region, the environmental degradation cost increased slightly with fluctuation from 18.1 to 19.8 billion US$ between 2011 and 2015. The regional environmental degradation index, on the other hand, gradually declined from 1.8 to 2.6% (Fig. 1). This ratio indicated the ratio between environmental degradation cost and GDP. The annual growth rate of the regional GDP over the years ranged from 7.8% to 9.4%, whereas the increase rate of the environmental degradation cost was only 0.04%, significantly lower than that of the GDP, leading to a decreasing environmental degradation index.

The degradation cost per unit land area and per capita also showed a slight increase throughout the years (Fig. 1).

3.2. Structural analysis of environmental degradation cost

Regarding different pollution media, the costs of environment degradation caused by air and water pollutions were relatively similar between 2011 and 2015, accounting for 52% and 48% of the total in 2011 and 2015, respectively. The degradation cost of atmospheric environment was mainly attributed to health economic loss and cleaning labor cost, both accounting for over 90% of total value between 2011 and 2015. The degradation cost of water environment was mainly caused by water shortage loss and health economic loss, both accounting for about 80% of the total between 2011 and 2015 (Fig. 1).

3.3. Distribution of environmental degradation cost

3.3.1. Total urban environmental degradation cost

Overall, the environmental degradation cost of each city within PRD region had little changes between 2011 (Fig. 2a) and 2015 (Fig. 2b), and thus we only focused to analyze the data of 2015 here. Guangzhou and Shenzhen were the two cities of highest environmental degradation cost, accounting for 58% together (5.5 billion US$) of the region in 2015. Foshan and Dongguan ranked the third and fourth, respectively, with the combined proportion of 22% in total for the two cities. The total degradation costs of Zhaoqing, Jiangmen and Huizhou accounted for 16% of the region, but the remaining two cities (i.e., Zhongshan and Zhuhai) accounted for 4% only (Fig. 2b). The environmental degradation cost of Shenzhen, Zhaoqing, Huizhou and Jiangmen were all dominated by degradation of water environment, while that of Guangzhou, Zhuhai, Foshan, Dongguan and Zhongshan were dominated by degradation of atmospheric environment (Fig. 2a and b).

The environmental degradation index of each city within PRD region had showed a decreasing trend to some extent. Especially for Shenzhen and Zhuhai during the study period (Fig. 2c and d). In 2015, Jiangmen and Zhaoqing had relatively high environmental degradation indexes, 2.6% for Jiangmen, and 3.3% for Zhaoqing, respectively, whereas Zhongshan and Zhuhai had very low indexes,

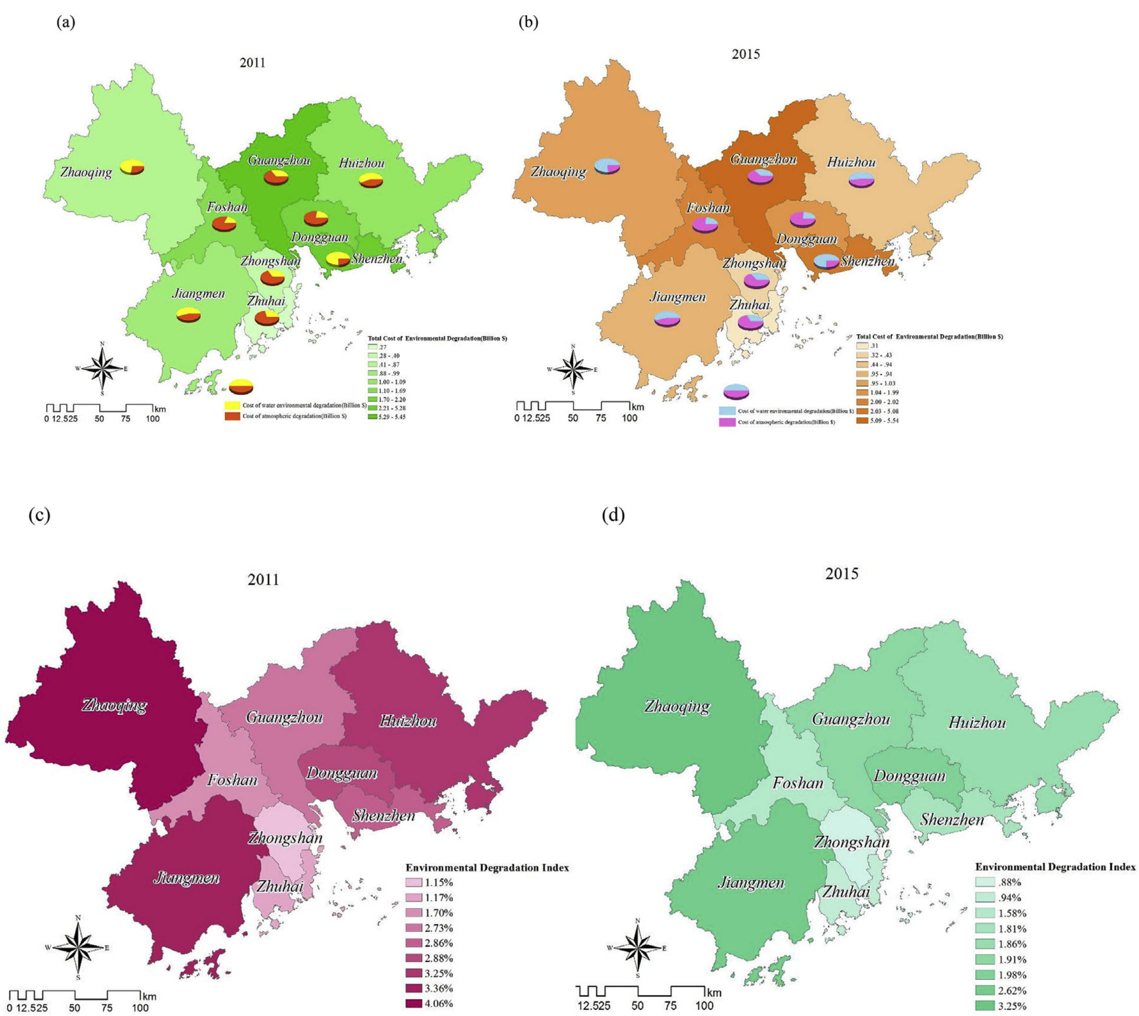

Fig. 2. Comparison of total environmental degradation cost and structural distribution of nine cities within PRD in (a) 2011 and (b) 2015, and comparison of environmental degradation index within PRD in (c) 2011 and (d) 2015.

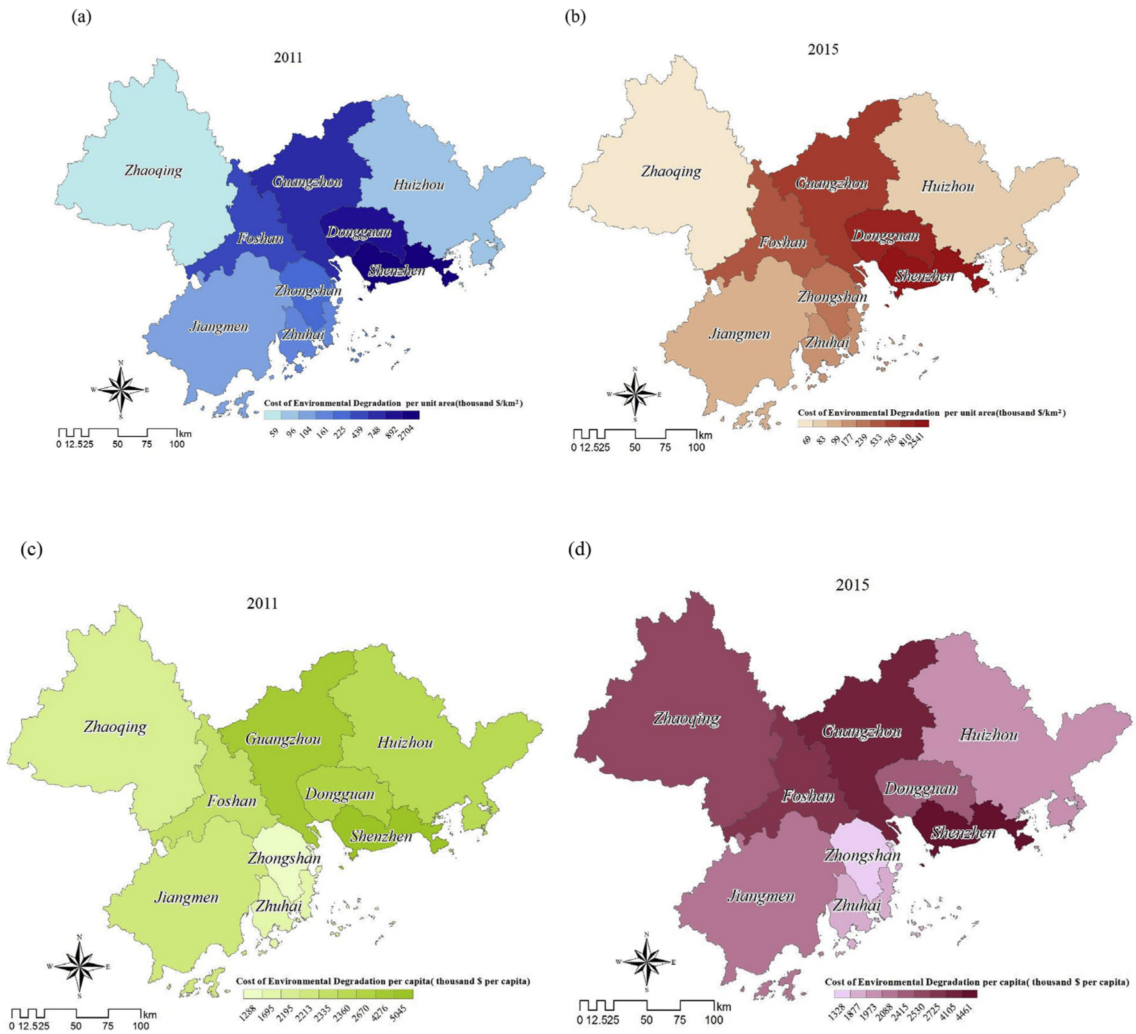

Fig. 3. Distribution of environmental degradation cost of unit land area of nine cities within PRD in (a) 2011 and (b) 2015, and distribution of environmental degradation cost per capita within PRD in (c) 2011 and (d) 2015.

both at around 0.9%. The indexes of Guangzhou, Shenzhen, Huizhou, Dongguan and Foshan ranged from 1.6% to 2.0% (Fig. 2d).

3.3.2. *Environmental degradation costs per unit land area and per capita*

The situations of environmental degradation intensity and per capita cost of each city within PRD region in 2015 were similar with those in 2011 (Fig. 3a, b, 3c, 3d). In 2015, Shenzhen had the highest degradation cost of unit land area, which was almost eight times higher than the average level of PRD region (Fig. 3b). Dongguan and Guangzhou also had relatively high level of degradation intensity, while Huizhou, Jiangmen and Zhaoqing showed a different trend. Concerning the per capita cost of environmental degradation in 2015, Shenzhen and Guangzhou were again the two highest cities, followed by Foshan, Zhaoqing and Dongguan (Fig. 3d). The remaining cities, such as Zhongshan and Zhuhai, were at the lowest level of per capita cost of environmental degradation.

3.3.3. *Dynamic change of urban environmental degradation cost*

From 2011 to 2015, Guangzhou and Shenzhen had always remained the top two of environmental degradation cost in PRD region, with different trends however. Guangzhou had increased by 2% while Shenzhen decreased by 4%. Zhongshan and Zhuhai remained at low cost level, though they had both increased to different extend (Fig. 4). The degradation cost of the rest five cities in PRD region had fluctuated slightly during the period. The environmental degradation costs of Foshan and Zhaoqing both had a growth by around 20%, but Dongguan, Huizhou and Jiangmen had a decline by various extents (Fig. 4).

4. Discussion

4.1. *Comparison with international accounting results*

World Bank launched pilot studies of environmental degradation cost accounting in Algeria, Egypt, Lebanon, Morocco, Syria and Tunisia focusing on land degradation and air pollution in 1999. The results indicated the losses ranged from 2.1% to 4.8% of national GDP (PRCEE et al., 2006). In 2013, World Bank expanded the study area to the seven regions of the world and evaluated their economic losses caused by air pollutions using personal willingness to pay (WTP) and income approach (Table 2) (World Bank, 2016). The results showed that the regional environmental degradation losses caused by air pollution accounted for 2.2%–7.5% of regional GDP in that year (World Bank, 2016). In comparison, the degradation index of atmospheric environment in PRD region in this paper, at only

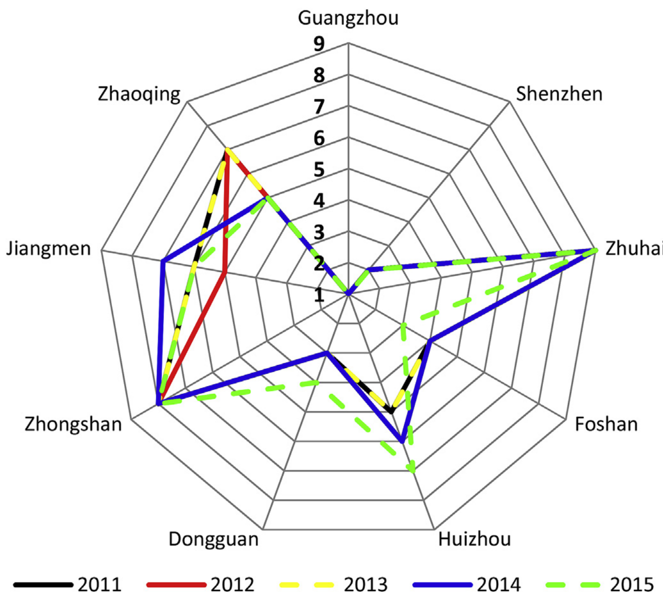

Fig. 4. Ranking of urban environmental degradation cost of nine cities within PRD from 2011 to 2015.

1.22%, is much lower than that of the seven regions. Likewise, the per capita atmospheric environmental degradation loss of PRD, reaching 184 US$/person, is also lower than most regions in North America, Europe and Central Asia. The degradation cost per unit land area in PRD region is however remarkably higher than that of the seven regions. It is because the accounting scope only covers the continent area of the PRD region and resulting in a relatively high degradation intensity.

However, the differences between the outcomes may largely resulted from the different valuation methods used in the accountings. This study, according to "green GDP2.0", took the methods of market value, replacement cost and income approach to evaluate economic costs. The results are generally lower than the results calculated by WTP, which is not constant and easily influenced by other factors (Baumgartner et al., 2016; Liu et al., 2013). The accountability and availability of data may also influence the comparability over the results, and thus the results and comparisons are for reference only.

4.2. Comparison with national accounting results

A complete accounting of green GDP has been done since the establish of China's green national economic accounting system. Based on the framework, the national pollution-induced economic loss accounted for 3.05% of GDP in 2004 (Wang, 2009). Regarding Guangdong Province, the total environmental degradation cost was 14.1 billion US$ in 2004, accounted for 2.89% of regional GDP (Wang, 2009). The top five cities in the province were Guangzhou, Shenzhen, Dongguan, Foshan and Shantou, together occupying 69.9% of the provincial cost (Wang, 2009).

In 2015, the national "green GDP2.0" accounting was launched. The results showed that the national environmental degradation index of China during 2011–2014 was within the range from 3.2% to 3.4%. Compared to the national accounting results, the environmental degradation index of PRD region in this paper is constantly lower than the national average level over the same period. The top four cities with the highest degradation cost in 2015 were Guangzhou, Shenzhen, Foshan and Dongguan, consistent with the results of the national accounting for Guangdong province in 2004.

The research led by Yu and his colleagues over the national environmental economic accounting for 2015 included a national environmental degradation cost accounting using the same calculating framework and methods of this study (Yu et al., 2017). The comparison of the results would therefore be highly reliable. The research led by Yu was done at a national level with specific results on each province in China, including Guangdong province. Our study, however, focused on the PRD region, a sub-region in Guangdong Province. In 2015, the average national environmental degradation index was at 2.94%, much higher than that of the PRD region, which indicates that the PRD region is leading a more balanced economic-environmental development than other regions (Table 3). The degradation loss per unit land area of the PRD region was, however, exceptionally higher than that of the other regions. This may be the results of the highly condensed industrial and urbanized development within the region.

4.3. Indications by environmental degradation index of PRD

The environmental degradation index of PRD region has remained at a rather low level, indicating that the ability of controlling environmental pollutions in PRD region has been continuously enhanced, and achievements have been gained in the green development and transformation. However, it also needs to be noticed that different cities within the region showed huge distances. The environmental degradation index of Zhongshan and Zhuhai in 2015, for instance, were both lower than 1%, whereas the index of Zhaoqing was beyond 3%.

Those cities with relatively low environmental degradation index, have gained more experiences in realizing coordinated development of economic growth and environmental protection (Wang et al., 2017). Considering the significant diversity in the

Table 2
Comparison of atmospheric environmental degradation within PRD area and other countries or regions in the world in 2013 (World Bank, 2016).

Countries/Regions	East Asia and the Pacific	Europe and Central Asia	Latin America and the Caribbean	Middle East and North Africa	North America	South Asia	Sub-Saharan Africa	Pearl River Delta (PRD) Area
GDP (10^8 US$)	212625	233492	62723	35240	185397	23569	16997	8607
Pollution (10^8 people)	22.5	9.0	6.2	4.1	3.5	17.0	9.5	0.6
Land Area (10^4 km^2)	2439	2744	2004	1124	1824	477	2362	5
Atmospheric environmental degradation cost (10^8 US$)	15947	11908	1505	775	5191	1744	646	105
Per capita atmospheric environmental degradation loss (US$/person)	709	1325	244	188	1477	103	68	184
Degradation loss of unit land area (10^3 US$/km^2)	65	43	8	7	28	37	3	192
Atmospheric environmental degradation index (%)	7.50	5.10	2.40	2.20	2.80	7.40	3.80	1.22

Table 3
Comparison of environmental degradation within PRD area and other regions in China in 2015 (Yu et al., 2017).

Regions	GDP (10^8 RMB)	Land Area (10^4 km^2)	Environmental degradation cost (10^8 RMB)	Per capita environmental degradation loss (RMB/person)	Degradation loss of unit land area (10^4 RMB/km^2)	Environmental degradation index (%)
Hebei	29806	18.8	1994	2685	106	6.69%
Ningxia	2912	6.6	173	2585	26	5.93%
Tibet	1026	122.8	48	1488	0.4	4.70%
Henan	37002	16.7	1565	1651	94	4.23%
Qinghai	2417	72.2	86	1456	1.2	3.54%
Shandong	63002	15.8	1993	2024	126	3.16%
Jiangsu	70116	10.7	1763	2211	164	2.51%
Zhejiang	42886	10.6	1019	1840	97	2.38%
Xinjiang	9325	163.2	218	922	1.3	2.33%
Yunnan	13619	39.4	288	608	7.3	2.12%
Guagndong	72813	18.1	1200		66.3	1.60%
Hainan	3703	3.5	35	384	10	0.95%
China	685506	963.4	20179	1468	21	2.94%
Pearl River Delta (PRD) Area	**62268**	**5.5**	**1138**	**1938**	**208**	**1.83%**

developing phases and mode, each city should, according to its resource endowment and industrial structure, take directed actions and targeted measures to improve ecological efficiency and eventually realize the win-win situation of economic development and environmental protection (Shi and Liu, 2013; Lu and Feng, 2015).

For the cities with relatively high environmental degradation index, such as Zhaoqing and Jiangmen, it is an urgent need to change the traditionally extensive development mode into a more sustainable and intensive one. Even though the resource and environmental constraints are relatively small now due to their good natural resource endowment, it would be doomed to face the challenge of environmental protection when resources being over consumed. Measures promoting sustainability, such as nurturing emerging green industries, improving ecological efficiency, enhancing energy structure etc., are therefore strongly suggested to be taken to improve the regional non-equilibrium of environmental performance.

For cities with average level of environmental degradation index, such as Guangzhou, Shenzhen and Huizhou, it is necessary to accelerate the process of environmental quality improvement. Those cities normally have certain basis for environmental protection, but there are too much pressures and rigid demands on economic development. Therefore, taking measures regarding technology upgrading and institutional reforming are suggested to promote the transformation of social economy and thus ultimately improving regional environmental quality.

5. Conclusion

Our study focused on the PRD region, one of the three major urban agglomerations in China. The regional development of PRD not only provides a vivid window and classic sample to study the major actions of the Chinese government in promoting ecological civilization construction and battling environmental issues, but also serves the effects of leading and demonstrating improvements to the other regions in China. According to the accounting results, the environmental degradation index showed a downward trend within PRD region during 2011–2015, with significant differences among cities.

The results indicate the environmental performance of PRD region has been continuously improved, which is a positive outcome by efforts taken by the government on pollution management. However, there still exits large differences among cities regarding the environment controlling capacity. The environmental degradation loss accounting is an important political tool for quantitatively representing regional green development and evaluating progress of ecological civilization construction. This study provides valuable application foundation for the accountability audit of natural resource and environmental performance evaluation of government in the future.

Acknowledgement

This work was partly supported by the Chinese Academy for Environmental Planning (CAEP) under the project on Constructing National GEP Accounting Framework (project. 2017A168).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2019.03.081.

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