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The impact of environmental regulations on urban Green innovation efficiency: The case of Xi'an

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ABSTRACT

While balancing economic progress and environmental pollution, environmental regulation plays a vital role conditioning green innovation. However, most research focuses on the effect of such regulations at the industry- or regional-level, lacking city-level analysis. Using the city of Xi'an (China) as a case study, environmental regulations and their effect on urban green innovation are analysed. First, using a slacks-based measure of directional distance functions (SBM-DDF) model we measure the green innovation efficiency of Xi'an from 2003 to 2016. Regression analysis is then used to explore the green innovation effect under the implementation of three environmental regulations, including command-and-control, market-based, and voluntary. Results indicate that market-based and voluntary regulations are more efficient at stimulating green innovation than command-and-control environmental regulations. The environmental regulations and green innovation efficiency also have non-linear inverted U-shape relationships. The findings will help policy makers to design more effective environmental regulations.

1. Introduction

Higher industrialization has contributed to the development of many urban economies, but this also has brought some environmental problems. Balancing a city's economic progress and its environmental preservation has been an important topic in the field of sustainable development for a long time. Of the indices used for measuring a region's sustainable development ability, one of the most prominent is green innovation (Bai, 2012; Liu, 2015; Zuo, Read, Pullen, & Shi, 2012). This index reflects an urban economy's sustainable competitive advantage.

Innovative urban development not only involves technological progress, but also the development of the environment. Similarly, cities, being accountable for a large proportion of total gas emissions, are usually among the first to adopt innovative sustainable practices that protect the environment (Dong, Gu, & Fujita, 2014; Yu, Shi, Zuo, & Chen, 2018). *Urban green innovation* involves a wide range of urban innovative activities aimed at stimulating a city's greener sustainable development. Urban green innovation can help cities gain an absolute competitive advantage for their economy (Fei, Wang, & Yang, 2016; Ryan, 2018). These may be some reasons why scholars are paying increasing attention to urban green innovation (OECD, 2011; Yang & Wang, 2009).

From a socio-political perspective, the sustainable development of a city is also related to a complex mechanism generated by the interaction of politics, economy and culture (Cumo, Astiaso Garcia, & Calcagnini, 2012; Morris, Zuo, Wang, & Wang, 2018). The socio-political behavior is very important in the process of building a green innovative city. The government takes political actions to push urban green development forward and must ensure the effectiveness of policies implementation. Namely, the goals of environmental regulations are transformed into specific strategies and institutionalized (Sum, 2005). Hence, urban environment and green innovation development are dealt with through regulatory incentives and policy frameworks (Bibri & Krogstie, 2016). Political action has a wide variety of political mechanisms and governance arrangements. They support and stimulate the role of environmental regulations in urban green innovation in

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different ways, such as: formulating policy tools and incentives to achieve urban change, authorizing specific organizations to legalize research activities, promoting government participation to achieve capital and market incentives, funding education and research institutions for the dissemination and utilization of knowledge and technology related to urban development, etc. (Bibri, 2015). All these create a favorable environment for urban innovation and promotes sustainable urbanization.

Therefore, many studies agree that effective environmental regulations can promote the sustainable development of a city, rectify undesirable externalities as environmental pollution, and stimulate green innovation within the industry (Nesta, Vona, & Nicolli, 2012; Yuan, Ren, Hu, & Yang, 2016). The latter is generally achieved by incorporating some degree of innovation in technology and its products, and realizing win-win ecological, social, and economic outcomes (Ambec, Cohen, & Elgie, 2013; Mickwitz, Heli Hyvättinen, & Kivimaa, 2008). However, different environmental regulations exist varying effectiveness on green innovation (Zhang, Wang, Xue, & Yang, 2018). Meanwhile, characteristics of the host country and its contextual factors are also influential (Bergek & Berggren, 2014; Ren, Li, & Yuan, 2018).

China is a country whose government has been recently passing many laws to stimulate more sustainable development, such as the Urban Greening Ordinance (revised in 2017), the Circular Economy Promotion Law (2009), and the Environmental Protection Law (revised in 2014). However, as with many other countries, China could fail in its attempt to stimulate a greener economy. India, for example, passed the Environmental Protection Act (1986), Air Act (1987 revision), and Water Act (1988 revision), and counts on a National Green Tribunal. However, that country's lack of a comprehensive environmental regulatory approach and critical evaluation of performance ended with citizens still suffering nowadays from many environmental problems (see Mejia, 2009). Hence, it seems obvious that it is not enough to seek green innovation just by passing environmental laws.

Extensive research has also been carried out on the innovation mechanisms behind environmental regulations. Most of them focus on processes and product innovation of some industries, and the role of environmental regulations in them (e.g. Guo, Zhou, Liu, & Wang, 2019; Tang, Zhong, & Xiang, 2019). For example, research on green innovation has traditionally focused on economic and ecological innovation in the medium and macro levels such as the industrial level and the national level (Khan, Sisi, & Siqun, 2019; Wang & Zhang, 2019). It has also focused on the micro level, such as company and product level (Borsatto & Amui, 2019; Liao, 2018). However, little research has been conducted on the relationship between different environmental regulation and green innovation from the urban perspective (city level of analysis).

Xi'an has been for a long time a Chinese paradigm of a city trying to stimulate innovative practices. The vast number of actions undertaken and the central position it occupies in China makes of Xi'an a representative example for analysis. Hence, the case study of Xi'an is analyzed to compare the effect on urban green innovation brought by different environmental regulations.

The structure of this paper is as follows. The next section reviews the research literature. In Section 3, the index system, data sources, and analysis model for representing the regression variables are described in detail. The next two Sections 4 and 5 describe and analyze the empirical results, respectively. Section 6 deals with policy recommendations, and Section 7 describes the conclusions and implications of this study.

2. Literature review

2.1. Urban green innovation

In innovation research, green innovation is crucial to social development and the transformation of urban environments (Fei et al., 2016). Green innovation is often connected with ecological modernization, sustainable development, and other environmental issues (Schiederig, Tietze, & Herstatt, 2012). Green innovation does not just mean reducing environmental problems, but also generating significant environmental benefits (Driessen & Hillebrand, 2002). Fussler and James (1996) were among the first to refer to it, emphasizing that green innovation drivers could explain the lack of innovation vitality of many companies. Kemp, Arundel, and Smith, (1998)) later defined green innovation as "new or improved processes, technologies, systems, and products resulting from avoiding or reducing environmental damage". This is now a commonly accepted definition, despite it is constrained to a micro-enterprise perspective. Chen, Lai, and Wen, (2006)) also analyzed the green innovation of products and manufacturing processes. Nowadays, green innovation also encompasses social and institutional innovation, including public participation, institutional structures, and the education system (CCICED, 2008).

Urban green development, on the other hand, is identified by many as the analysis of pollutant emissions and energy resource constraints (Glaeser & Kahn, 2010; Ji, Li, & Jones, 2017). Similarly, but from an innovation perspective, many papers have also focused on the construction of innovative cities or green development index systems (e.g., the GIE) as well as on the assessment of urban innovation ability (e.g. R &D funding, education and economy performance, technological innovative capabilities, etc.) (Liu, 2015; Sun, Tong, & Zou, 2018).

In what follows, stemming from the dominant input-output approach of most research into innovation, it is assumed that urban green innovation aims at obtaining more economic benefits, technological progress, and greener city spaces with the same (or lower) investment in economic capital, human resources, energy, and pollutant emissions. By this definition, urban green innovation pursues the maximization of economic, social, and environmental benefits, while promoting sustainable urban development.

2.2. Types of environmental regulation

Environmental regulation is generally understood as the concretization of a sustainable development and environmental protection strategy (Chen & Härdle, 2014). It provides the guidelines for restraining and coordinating the perception, uses, and aims of environmentally-regulated objects. It can also effectively improve environmental quality, while also offsetting the regulatory costs arising from pollution control (Ribeiro & Kruglianskas, 2015). In general, environmental regulations are classified into three groups: command-and-control, market-based, and voluntary (Ren, Li, & Yuan, 2018).

From a regulatory and mandatory perspective, command-and-control regulations involve legislation that states what is permitted and what is illegal. They include environmental laws and regulations, product and technical standards, bans, and environmental assessment systems. This type of regulation is widely used in China.

Market-based regulation means that government uses prices as a market-oriented mean to achieve higher pollution control efficiency at a lower cost. From this perspective, environmental regulations include environmental taxes and fees, subsidies, market bonds, emissions trading, and ecological compensation systems.

Finally, from the perspective of participation mechanisms, voluntary environmental regulations provide important instruments of regulation through public participation. These include information disclosure, environmental labels, environmental letters and visits, and transparent publicity, to cite a few.

2.3. Research gap

Despite the importance of environmental regulation is widely recognized and researched, most research analyses have concentrated on the innovation effect of environmental regulations at the enterprise or industry level. Research on how environmental regulations promote the development of green innovation in urban settings is still relatively scarce. It is anticipated that different environmental regulations can promote different green innovation efficiency outcomes too. However, it is unclear what these relationships might be like, especially when previous results from the industry and enterprises are sometimes contradictory.

Xi'an has experienced significant economic and innovation changes over the last 15 years. Hence, it is an exemplar likely to constitute a very interesting and representative case study. Consequently, Xi'an is used to explore the effects on urban green innovation efficiency of the three broad groups of environmental regulation (command-and-control, market-based, and voluntary).

3. Materials and methods

This study uses an explanatory case study to analyze the relationship between environmental regulation and urban green innovation. It also resorts to Data Envelopment Analysis (DEA) and regression techniques for deeper data analysis. Some robustness tests are also implemented to test the results validity. The purpose and implementation of each of them will be outlined as they are introduced.

3.1. Case study

A case study is a common empirical research method, which can comprehensively investigate complex and specific problems in the reality (Yin, 2007). Particularly, explanatory case studies aim at summarizing phenomena and extract some conclusions which are suitable for a first relevance or causality analysis (Eisenhardt, 1989).

Here, we selected Xi'an to analyze green innovation and the effects of environmental regulation in it. Xi'an is one of the top ten innovative cities in China (Meng, 2018). It has 63 colleges and universities, 3000 scientific research institutions, and over 40 national laboratories employing more than 460,000 professional and technical personnel (Meng, 2018). The city has introduced many policies in recent years to stimulate innovation and entrepreneurial development. These policies have contributed to the construction of innovation platforms (Li, Zhang, & Wang, 2018). The 2018 China Urban Innovation Competitiveness Development Report (Huang, 2018) ranked Xi'an's urban innovation competitiveness eighth in the country, being one the most innovative cities compared to other cities located in central and western regions. Meanwhile, much literature has described Xi'an as a city to carry out research on technological innovation (Li, Zhang, & Osei, 2018; Wang & Zhou, 2015) because of its creative industry (Shan & Li, 2011), innovation atmosphere (Xie, Xue, & Li, 2018), and innovation performance (Xie, Mao, & Zhang, 2011). For all these reasons, we expect the city chosen is a good exemplar to draw some exploratory conclusions on the effect of environmental regulations on urban green innovation.

3.2. Urban green innovation efficiency analysis with SBM-DDF

Data Envelopment Analysis (DEA) has been used for the analysis of production efficiency, as it is capable of handling multiple inputs and outputs (Zhang, Liu, & Bressers, 2011). Many studies have used DEA to analyze environmental pollution and energy consumption, mostly considering them as inputs (Reinhard, Lovell, & Thijssen, 1999) or undesirable outputs (Sueyoshi & Goto, 2013), and frequently with the intention of measuring efficiency under particular environmental constraints (Ramanathan, 2005).

Within DEA models, the direction distance function (DDF) is one of the most popular techniques. It allows considering the effects of desirable and undesirable outputs separately (Li & Wu, 2016; Pal & Mitra, 2016). More precisely, each Decision making unit (DMU) is assumed to get a set of M desirable outputs and K undesirable outputs when N inputs are used. x refers to inputs, y and d are specific desirable and undesirable outputs, whereas $P(x)$ is defined as the set of production possibilities, which is expressed as:

$$\mathrm{P(x)}=\{(x, y, d)\text{: x produce } (y, d),\ \ x \in R_N^+,\ \ y \in R_M^+, d \in R_K^+\} \tag{1}$$

DDF can help increasing the desirable output and reducing the undesirable output simultaneously (Chung, Färe, & Grosskopf, 1997). Particularly, letting directional vector $g = (g_y, \text{-}g_d)$, β is the ratio of two types of outputs, giving:

$$\overrightarrow{D_0}(x, y, d; g) = \sup\{\beta\text{: } [(y, d) + \beta g] \in P(x)\} \tag{2}$$

Furthermore, a slacks-based measure (SBM) model contains slack variables of input and output. Based on research by Fukuyama and Weber (2009) and Färe, Grosskopf, and Pasurka, (2007)), SBM can be further combined with DDF to prevent DDF models' radial character and directivity be effectively avoided. With this, a traditional DDF model's overestimation of efficiency can be reduced (Arabi, Munisamy, & Emrouznejad, 2015; Li, Zhang, Osei et al., 2018).

Hence, the slacks-based measure of directional distance functions (SBM-DDF) considering undesirable outputs are defined as:

$$\begin{gathered}\vec{D}_0^t(x^t, y^t, d^t, g^x, g^y, g^d)\\ = \max_{s^x,s^y,s^d} \frac{\frac{1}{N}\sum_N^{n=1} \frac{s_n^x}{g_n^x} + \frac{1}{M+1}\left[\sum_M^{m=1} \frac{s_m^y}{g_m^y} + \sum_K^{k=1} \frac{s_k^d}{g_k^d}\right]}{2}\\ \text{s.t} \sum_{j=1}^J z_j^t x_{jn}^t + s_n^t = x_{j'n}^t, \forall\ n; \sum_{j=1}^J z_j^t y_{jm}^t + s_m^t = x_{j'm}^t, \forall\ m;\\ \sum_{j=1}^J z_j^t x_{jk}^t + s_k^t = x_{j'k}^t, \forall\ k; \sum_{j=1}^J z_j^t \geq 0, \forall\ j;\\ s_n^x \geq 0, \forall\ n; s_m^y \geq 0, \forall\ m; s_k^d \geq 0, \forall\ k\end{gathered} \tag{3}$$

Where j represents the number of decision-making units, z_j^t is the weight of period t, and (x^t, y^t, d^t) 、(g^x, g^y, g^d) 、(s^x, s^y, s^d) are the input-output, directional and slack vectors, respectively.

3.3. Regression model construction

3.3.1. Classic theory model

We will also resort to a regression model built on the STIRPAT model. The latter was proposed by Dietz and Rosa (1997) and has been widely used to study environmental pollution and economic development. The STIRPAT model is as follows:

$$\mathrm{I} = \alpha P^b A^c T^d e \tag{4}$$

The STIRPAT is a multivariate model, which involve the variables: population (P), affluence (A), and technology (T). However, a logarithmic transformation of formula (4) is generally adopted:

$$\ln I = \ln\alpha + b\ln P + c\ln A + d\ln T + \ln e \tag{5}$$

Where α is a constant term; e is the error term; and b, c, d are the estimated terms. This model can also be used for multivariate linear fitting.

3.3.2. Extended model

Building on the model above, this study analyzes urban green innovation efficiency (UGIE) (as dependent variable) and adds different types of environmental regulations (independent variables) into the model. P is represented by the average number of higher education students; A is represented by the foreign direct investment; whereas T is the government investment in science and technology. All these are important factors affecting green innovation and will be duly justified later. In the model, they are treated as control variables.

With all this information, the first regression model will be:

$$\mathrm{UGIE}_t = \alpha + \beta_1 \ln \mathrm{CER}_t + \beta_2 \ln MER_t + \beta_3 \ln VER_t + \beta_4 \ln CV_t + \varepsilon_t \tag{6}$$

Additionally, a quadratic term for the environmental regulation effects is added to explore the potential non-linear relationships between variables. This non-linear (quadratic) model is as follows：

$$UGIE_t = \alpha + \beta_1 \ln ER_t + \beta_2 (\ln ER_t)^2 + \beta_3 \ln CV_t + \varepsilon_t \tag{7}$$

Table 1
Index system summary of urban green innovation efficiency.

Index	Index name	Measured by	Unit	Also adopted by (Source)
Input index	Labor input	R&D Personnel	Person	Li, Zhang, Wang et al. (2018) and Kneller and Manderson (2012);
	Financial input	R&D expenditure	10,000 Yuan	Feng, Shi, and Kang (2017); Song et al. (2015)
	Resource input	Total gas supply in urban areas	Tons	Li and Wu (2016)
Desirable output index	Scientific and technological output	Number of granted invention patents	Units	Fankhauser, Bowen, and Calel (2013); Yabar, Uwasu, and Hara (2013)
	Economic output	GDP per capita	Yuan/Person	Feng et al. (2017)
	Greening output	Green rate	%	Langemeyer, Baró, and Roebeling (2015)
Undesirable output index	Environmental output	SO_2 emissions	Tons	Managi and Kaneko (2006); Zhang et al. (2011)

Where t presents the year (t=year 1, 2, 3…14); $UGIE$represents the urban green innovation efficiency of Xi'an; lnER represents a specific type of environmental regulation in Xi'an; lnCER represents the command-and-control environmental regulation; lnMERrepresents the market-based environmental regulation; lnVER represents the voluntary environmental regulation; lnCV represents other control variables; α is the regression model intercept; and ε_t is a random error item. The way all these variables are measured is explained in the next section.

3.4. Regression variables

3.4.1. Urban green innovation efficiency (dependent variables)

Different combinations of input and output variables may produce different evaluation results (Song, Tao, & Wang, 2015). This is why it is particularly important to build a sound index system to evaluate green innovation. As Yuan and Xiang (2018) and Li and Wu (2016) did, urban green innovation efficiency is measured by establishing an index system of multiple inputs and multiple outputs. They are summarized in Table 1.

A thorough justification and further details of all the variables listed in Table 1 are presented as Supplemental Online material. For the sake of clarity and brevity, though, they have been left out of the main manuscript.

3.4.2. Environmental regulations indices

The indicators of *Command-and-control* environmental regulation generally include emission standards, laws, utilization and disposal rates, etc. However, environmental regulation laws and standards usually remain stable for long periods and cannot reflect changes shortly after new environmental regulations are introduced (Huang & Liu, 2014). Additionally, lack of reliable data concerning the standard rates of pollutants registered in Xi'an prevents this approach. Instead, following Xie, Yuan, and Huang, (2017)) approach, the amount of environmental investments made by companies in environmental protection (pollution control mostly) is adopted.

Market-based environmental regulations are policy instruments (generally price and cost incentives) to encourage polluters to reduce or eliminate negative environmental externalities. Although cities in a few pilot provinces use environmental subsidies, market bonds, and emissions trading, Xi'an was not one of them. However, pollution discharge fee has been levied from 1982 and is therefore used to represent market-based regulations.

Finally, *Voluntary* environmental regulation aims at consciously protecting the environment and supervising companies and regulatory agencies through environmental information. Voluntary environmental regulations can be measured by environmental labels, environmental information disclosure, pollution complaints, etc. Here, following Kathuria (2007), we choose the number of environmental news items relating to environmental pollution to present voluntary environmental regulation.

3.4.3. Control variables

Many factors influence urban green innovation efficiency in addition to the three types of environmental regulation stated above. According to the research of Yuan and Xiang (2018) and Li, Zhang, Wang et al. (2018), control variables in this paper contain foreign direct investment, regional education level, and government support.

In the context of international openness and trade, the attraction of *foreign direct investment* (FDI) is highly desirable for developing countries (Newman, Rand, Talbot, & Tarp, 2015). This investment is often accompanied by the adoption of new technologies and innovations, which can make up for the shortage of funds in the urban scientific and technological innovation landscape in the short run. The control variable FDI is therefore chosen in this study.

Education provides the human capital needed for a country's innovation system, which also encompasses green innovation. As the quality of university graduates is generally high (Yang, Zhang, & Rong, 2011), their number should fully reflect the level of local education. *Regional education level* is therefore represented by the amount of higher students (EDU), including undergraduate and postgraduate students studying in Xi'an.

Government support is crucial for the development of cities and its funding is irreplaceable in the process of innovation, as it reduces the cost and risk of research and stimulates R&D initiatives (Li, Zhang, Osei et al., 2018). This variable is therefore represented by government investment in science and technology (GIST).

3.5. Real data collection

According to Yin (2007), multiple sources of information strengthen the validity of a study. This study resorted to interviews, datasets, documents and reports from 2003 to 2016 to study the efficiency of green innovation in Xi'an and the effect of different environmental regulations (data from 2017 onwards had not yet been all published as of the submission of this manuscript). Namely:

(1) Datasets. Data on Xi'an's R&D personnel, total gas supply, R&D expenditure, number of granted invention patents, GDP per capita, green rate, SO_2 emissions, environmental investments in environmental protection, foreign direct investment, number of higher education students, and government investment were collected from Xi'an's statistical yearbooks (2004-2017) and the China city statistical yearbooks (2004-2017).
(2) Documents and reports. Data on pollution discharge fees and the number of environmental news items were obtained from the of Xi'an's ecology and environment bureau website (http://xaepb.xa.gov.cn/ptl/index.html), as well as from regional environmental reports.
(3) Interviews. This study also held some focus-group interviews to better understand some stakeholders' views on the role of different types of environmental regulations in Xi'an's green innovation. Rabiee (2004) pointed out that 6–8 people are generally the best choice for focus-groups interviews, thus six people were selected. Interviewees included government officials, business managers,

Table 2
Summary of interviewees' profiles and interviews content.

Number	Interviewee	Department	Working years	Educational background	Interview content highlights
#1	Government official	Municipal government	8 years	Postgraduate	At present, Xi'an's mandatory laws and regulations, incentive environmental policies can effectively promote the urban high-quality development. Xi'an's environmental governance and innovative development have made remarkable achievements.
#2	Government official	Ecology and environment	5 years	Postgraduate	Implement environmental supervision and law enforcement in Xi'an city, and impose administrative penalties on those who have environmental violations or fail to meet the emission standards, so as to promote the development of green innovation in Xi'an and build a greener, more innovative and ecological Xi'an.
#3	Business manager	Administration	3 years	Postgraduate	With the implementation of the government's incentive policy, enterprises have been encouraged to carry out green innovation, but independently from each other. However, this has resulted in greener technologies, and product and management innovation. It has significantly improved profits and productivity, and now enterprises have some absolute competitive advantages.
#4	Scientist	Technology innovation	4 years	Doctorate	Under the influence of environmental regulations, enterprises in Xi'an have increased the investment on technical personnel and capital to reduce pollutant emissions through technological innovation, and meet the standards requirements. Research on green innovative products is beneficial to both companies and the environment.
#5	Journalist	TV stations	6 years	Graduate	Media reports on the pollutant discharges of key urban pollutant enterprises, plus mass petition letters, visits and information disclosure, effectively curb urban pollution behavior.
#6	Volunteer	Organization volunteer	3 years	Graduate	Actively participating in volunteer activities related to environmental protection, and raising awareness of environmental protection, help Xi'an's citizens to promote and receive suggestions for urban green development.

Table 3
Urban green innovation efficiency in Xi'an.

Year	Comprehensive efficiency	Purely technological efficiency	Scale efficiency	Return of scale
2003	1.000	1.000	1.000	Constant
2004	1.000	1.000	1.000	Constant
2005	0.815	0.816	0.999	Decreasing
2006	1.000	1.000	1.000	Constant
2007	0.961	1.000	0.961	Decreasing
2008	1.000	1.000	1.000	Constant
2009	1.000	1.000	1.000	Constant
2010	1.000	1.000	1.000	Constant
2011	1.000	1.000	1.000	Constant
2012	0.841	0.849	0.990	Increasing
2013	1.000	1.000	1.000	Constant
2014	0.714	0.722	0.989	Increasing
2015	1.000	1.000	1.000	Constant
2016	1.000	1.000	1.000	Constant
Average	0.952	0.956	0.996	

scientific researchers, journalists and volunteers. The selection criteria of interviewees were the following: first, select the people closely related to Xi'an green development (for representativity purposes). Second, select the people from different industries and departments (for diversity purposes). Finally, choose people with minimum education level and working experience (for validity purposes). The collection methods of interview data were face-to-face recordings and notes in up to 90-minute interviews. The contents of these interview are summarized in Table 2.

4. Results

4.1. Urban green innovation efficiency

Implementing the SBM-DDF model, estimates of 2003–2016 green innovation efficiency are presented in Table 3. They were obtained using Maxdea® software. Table 3 contains four headings: comprehensive efficiency, purely technological efficiency, scale efficiency, and return of scale. *Comprehensive efficiency* represents technical efficiency without considering returns of scale. It equals the scale efficiency multiplied by the purely technological efficiency. *Purely technological efficiency* reflects the effectiveness of decision-making and management. *Scale efficiency* values are the result of a change of scale. Finally, *return of scale* is used to analyze the changes in output caused by the same proportion of internal production factors, which comprises three situations (increasing, decreasing, and constant returns).

As can be seen, the average comprehensive, purely technological, and scale efficiency were 0.952, 0.956, and 0.996, respectively. The very high scale efficiency evidences that the scale of green innovation activities was effective, and that returns remain constant most years.

In 2003, 2004, 2006, 2008–2011, 2013, 2015, and 2016, comprehensive, purely technological, and scale efficiency were all unity. This indicates that the input and output of urban green innovations were at the front of the production frontier (input resources fully utilized and optimal scale returns). In 2007, purely technological efficiency was equal to unity, but the scale return decreased. That indicated that the innovation foundation and practice were relatively mature at that time. However, the scale was unreasonable and input and output were disproportionate. This meant a small change in input was needed to cause an improvement in green innovation. In 2005, 2012, and 2014, purely technological efficiency was lower than scale efficiency, being the impact of scale efficiency greater than technological efficiency.

Table 4
Unit root test results.

Variables	Method	Statistic	P-value
UGIE	ADF	−4.6087	0.0039
	PP	−4.6231	0.0039
lnCER	ADF	−4.9093	0.0043
	PP	−12.4504	0.0000
lnMER	ADF	−4.3106	0.0074
	PP	−4.3929	0.0065
lnVER	ADF	−5.1788	0.0019
	PP	−5.6558	0.0009
lnFDI	ADF	−3.3268	0.0372
	PP	−7.7004	0.0001
lnEDU	ADF	−3.4608	0.0280
	PP	−3.4608	0.0280
lnGIST	ADF	−3.8718	0.0151
	PP	−5.0828	0.0022

4.2. Regression analysis

4.2.1. Unit root test

Phillips-Perron (PP) and Dickey-Fuller (DF) tests were used to analyze the data stability of this study. Table 4 shows that all P values remained below 0.05. This rejects the null hypothesis that there is a unit root in a time series sample, meaning all variables can be deemed stable and that the data is suitable for empirical analysis.

4.2.2. Regression results and analysis

Tobit regression was necessary for expressions (6) and (7). Calculations were carried out with Eviews 8® software, and Table 5 shows the regression analysis results of the Tobit model.

Table 4 shows that the P value of the variable lnCER is very high. Its regression coefficient is very close to zero, indicating that the increase of command-and-control environmental regulation neither stimulates nor inhibits urban green innovation efficiency. Compared with command-and-control environmental regulation, the P value of variable lnMER is 0.060 with a significance level of 0.1. Its positive coefficient (0.1252) evidences a significant stimulating effect of market-based environmental regulations on urban green innovation efficiency. Furthermore, among the environmental regulations, voluntary regulations seem to have the most significant impact (lowest P value too) on urban green innovation efficiency. Its coefficient (0.4601) is comparatively larger than the previous two.

Concerning the impact of the other control variables, FDI significantly influences green innovation (0.2626). Foreign enterprises use advanced production equipment, technology, and management experience. Meanwhile, the city can effectively avoid the negative crowding-out effect caused by the FDI with a strong economic and technological foundation. Therefore, FDI can apparently improve green innovation through imitation and competition.

The regional education level has a significant and negative effect (-1.9668). Citizens and graduates do not seem to be consider the task of green innovation urgent, nor there is a high demand for green development and technological improvement. All this may have inhibited the development of green innovation in Xi'an.

The coefficient of government support is not significant, indicating that government support does not have a significant impact. This may be due to the city's weak green innovation power and its limited absorptive capacity. Alternatively, the amount of government support may have been insufficient due to expenditure on other innovative activities, further reducing overall investment in green innovation.

At the same time, we used the quadratic model from expression (7) to test other non-linear relationships. Table 6 shows different non-linear regression analysis results from models 1–3.

Table 6
Non-linear regression analysis results.

Variables	Model 1	Model 2	Model 3
lnCER	3.5534**		
$\ln^2$(CER)	−0.1877**		
lnMER		2.7546***	
$\ln^2$(MER)		−0.1556***	
lnVER			7.3916*
$\ln^2$(VER)			−0.7149*
lnFDI	0.9168***	0.8682***	0.2027**
lnEDU	−2.4675***	−2.2582***	−0.2654
lnGIST	−0.1853	−0.0448	−0.1658
α	−7.7336	−5.5163	−16.7804
Curve type	Inverted U	Inverted U	Inverted U
Log likelihood	15.3276	19.0001	13.1247

Note: ***, **, and * denotes significant levels of 1%, 5%, and 10 % respectively.

Model 1 contains linear and quadratic variables for command-and-control environmental regulations. Results indicates that coefficients of ln(CER) (linear term) is significant and positive while $\ln^2$(CER) (quadratic term) is negative. This finding means that the relationship between environmental regulation and the efficiency of green innovation is an inverted U. This indicates that command-and-control environmental regulations stimulate green innovation in the initial stage (maybe because companies and institutions immediately react to new legal constraints and meet prescribed emission standards). However, when environmental regulation exceeds a certain level, obligations significantly increase the cost burden of environmental pollution control and its efficiency is reduced.

Model 2 shows that the coefficients of linear and quadratic terms are significantly positive and negative respectively, again showing the same inverted U-shape relationships as in model 1. Similarly, urban green innovation efficiency increases with the enforcement and improvement of market-based environmental regulations, but there is a progressive deterioration regarding its efficiency gains.

The coefficients of voluntary environmental regulation are both significant in Model 3, which again shows that voluntary environmental regulation has an inverted U-shaped effect on green innovation efficiency. It indicates that voluntary regulations are initially effective, but their effectiveness are also reduced as more voluntary regulations are passed over time.

Finally, as for control variables, FDI has a significant positive effect

Table 5
Regression analysis results.

Index	Variables	Coefficient	Standard error	Z-value	P-value
Command-and-control env. reg.	ln CER	0.0022	0.0613	0.0351	0.9720
Market-based env. reg.	lnMER	0.1252*	0.0666	1.8810	0.0600
Voluntary environmental reg.	lnVER	0.4601***	0.1744	2.6382	0.0083
Foreign direct investment	lnFDI	0.2626*	0.1554	1.6905	0.0909
Regional education level	lnEDU	−1.9668***	0.7317	2.6880	0.0072
Government support	lnGIST	−0.0944	0.1387	0.6807	0.4961
Constant	α	8.713***	3.0097	2.8949	0.0038

Note: ***, **, and * denotes significant levels of 1%, 5%, and 10 % respectively.

in Models 1 and 2, while regional education level has a significant negative effect in all cases.

4.3. Robustness test

In this study, we also implemented a series of robustness tests in the regression models. Particularly, we used the robust least squares method to check whether the impacts of environmental regulation on green innovation had changed over time.

The robustness test results are shown in the Supplemental Online material. From their analysis it can be found that the regression results can be considered robust and data have remained relatively stable over the whole period of analysis.

5. Discussion

This study explores the linear and nonlinear relationships between three types of environmental regulations and green innovation efficiency at the city level of Xi'an. The results show that there is no direct impact of the type of regulation on green innovation efficiency in the linear analysis. However, it is found in the non-linear analyses, that the three types of environmental regulations are all intrinsically connected by means of inverted U-shape relationships with green innovation efficiency. Particularly:

Command-and-control environmental regulation absence of linear correlation with green innovation efficiency is not consistent with the recent Zhang et al.'s (2018) analyses. However, the existence of a non-linear relationship might mean that when command-and-control regulations are implemented, companies and institutions usually rush into adopting new environmental strategies. They directly accept government-designated pollution reduction technologies and environmental standards, but lack freedom to choose the technologies they want to achieve those new goals (Song, Zhang, & An, 2013). Once they meet the emission reduction standards, companies regain freedom to choose how to keep reducing emissions (Pan, Ai, & Li, 2017). These effects tend to reduce the added value of innovative strategies and the investment of funds for scientific and technological innovation. Also, these unintended outcomes render the development and technological progress of cities more difficult, possibly mitigating the positive environmental effects of enforcing this type of legislation.

Regarding market-based environmental regulation, their significant linear and non-linear connection with green innovation efficiency are in line with Jaffe, Newell, and Stavins (2005). They found that environmental regulation, such as carbon emission trading system, taxes and so on, can incentivize technological change. Indeed, many scholars agree that this incentive-oriented policy has a more obvious promoting effect than the mandatory regulatory (Pan et al., 2017). This, because market-based environmental regulations are generally linked to product output restrictions and sewage discharge through taxes, fees, etc. This means regulatory costs are more reflected in the production process (Zhang et al., 2018; Zhao & Sun, 2016). Hence, under the influence of market-based environmental regulations, a city prioritizes the investments in better environmental technologies that meet the government's regulatory requirements. This balances their economic and environmental performance. In other words, market-based regulation produces strong innovation incentives that protect the environment more effectively. Market incentives can also better mobilize the enthusiasm of companies and institutions, and effectively combine their strengths to make decisions about the optimal input-output and pollution emissions (Zhao, Zhao, & Zeng, 2015), but even those entities' innovation capabilities have some limits, which is why they decrease over time.

Lastly, the significant linear and non-linear relationship between voluntary environmental regulations and green innovation efficiency aligns with Lim and Prakash (2014) results. They used ISO 14001 participation levels as a proxy for regulation, finding that the adoption of the ISO 14001 is relevant to innovation. They also showed that green innovation efficiency can be more effectively stimulated by voluntary environmental regulations. The main reason being that voluntary environmental regulation cannot only alleviate regulatory pressure, but also invite enterprises and institutions to develop their own energy conservation and emission reduction plan (Lim & Prakash, 2014). The latter helps building a mutual trust between enterprises and regulators (Ball, Burt, De Vries, & MacEachern, 2018). However, this kind of regulation also has a spillover effect. When it exceeds a certain level, the investment of enterprises comes to a limit and the promotion effect is reduced.

6. Policy recommendations

According to the results and discussions of this study, policy makers should understand the different levels of effectiveness of these regulations and optimize them so as to make better-informed decisions. Mandatory command-and-control environmental regulation will lead to a lack of options for green innovation technologies for companies, while market-based environmental regulation takes into account emission reduction costs and encourages companies to adequately allocate resources in the market. This means economic instruments are more conducive to green innovation than setting compulsory environmental standards and emission limits. Policy makers could actively apply market-based environmental regulations to improve the market platform of regional industries and promote pilot trials of new emission taxes and carbon trading to ultimately achieve greater pollution control.

7. Conclusion

It is necessary to encourage green innovation by effectively designing environmental regulations that stimulate urban green transformation. With the case study of Xi'an, this study analyses the changes and influences of three environmental regulations on urban green innovation. Results show that command-and-control environmental regulations restrain the growth of green innovation, mostly because of their implementation costs. Market-based and voluntary environmental regulations, on the other hand, significantly stimulate green innovation efficiency. With improvement of market mechanisms, and particularly by increasing the environmental awareness of companies and public, voluntary environmental regulations have the most noticeable incentivizing linear effect on green innovation. The three types of environmental regulations also have an inverted U relationship with green innovation efficiency. Finally, considering other factors influencing urban green innovation, it is found that the level of regional education is significantly but inversely correlated with green innovation efficiency, international openness is positively and significantly correlated, whereas government support has no significant impact.

The theoretical contribution of this study lies in, firstly, focusing on the effect of environmental regulations on green innovation at the urban level in the developing country like China. Secondly, understanding the non-linear effects of three environmental regulations on urban green innovation efficiency.

There are also some limitations to be considered. First, due to the unavailability of some statistical data from the early years in the time series analyzed, the analysis of the link between environmental regulations and green innovation is not exhaustive. Secondly, the input and output factors of urban green innovation and the environmental factors used in this study as regression variables are complex and multifaceted factors. A simplified approach was adopted here to represent their major traits with the information available. In future research, more environmental variables may be needed to increase the model's reliability and accuracy.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.scs.2020.102123.

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