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RESEARCH ARTICLE

# Is environmental regulation effective in promoting the quantity and quality of green innovation?

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## Abstract

Green innovation (GI) is an important means of achieving a win-win outcome in the form of both economic development and environmental protection. Using a unique Chinese Patent Census Database to identify the quantity and quality of GI in each province and panel data for Chinese industrial sector in 30 provinces from 2002 to 2015, we investigated the impact of environmental regulation (ER) on GI in China. This study presents the first attempt to identify green innovation quality in China. Empirical results show that there is an inverted-U relationship between ER and GI. The heterogenous effects are further investigated in order to obtain more accurate policy implications. The results indicate that the impact of ER on GI is insignificant in the central and western regions, implying the necessity of adjusting ER policies in these regions. Second, the inverted *U*-shaped relationship between ER and GI only occurred in provinces with high state-owned enterprise (SOE) ratio, figuring out the special role of Chinese SOEs in promoting GI. Third, the impact of ER on GI is insignificant in regions with high levels of pollution, indicating high potential of green innovation and policy adjustments there.

**Keywords** Green innovations · Patent quality · Environmental regulation · State-owned enterprises · Pollution

## Introduction

The use of natural resources alongside pollution mitigation has been an important topic for economic research (Jerónimo Silvestre et al. 2018; Fedulova et al. 2019). Since the reform and opening up in 1978, China has experienced rapid economic growth but severe environmental deterioration. According to data from the World Bank, the average

**Highlights** • This study attempts to identify green innovation quality in China.
• An inverted *U*-shaped relationship between ER and GI is observed in some regions.
• The impact of ER on GI is insignificant in regions with high levels of pollution.

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annual growth rate of gross domestic product (GDP) (constant 2010 US$) in China is 9.37% from 1978 to 2019, much higher than that in the world (2.91%) during the same period, and China has become the second largest economy in the world. In other words, China has increasingly become the engine of global economy.

However, China's economic achievements involving high energy consumption, high emissions, and high pollution have come at the expense of the environment (Shan and Wang 2019), which is a kind of "black" economic growth. According to the Environmental Performance Index (EPI) report, China's EPI score and ranking have been relatively low since the report was first released in 2004. In 2018, China had an EPI score of 50.74 and ranked 120th out of the 180 countries surveyed.

In fact, many regions and industries in China are still relying on a development model characterized by high investment, high emissions, and high pollution in pursuit of rapid economic growth, leading to increasingly severe environmental problems and unsustainable development (Zhu et al. 2019; Wang et al. 2020; Du et al. 2020; Ji et al. 2019). How to mitigate environmental pollution in the process of economic development has become a major challenge for China and even the world (Ge et al. 2020).

Considering the public good character of environment, neither consumers nor producers are willing to pay for environmental damage. Therefore, it is necessary for governments to adopt external regulatory measures to limit human degradation of the environment. Environmental regulation (ER) involves a range of environmental protection policies aimed at achieving sustainable economic and social development (Liu and Xie 2020). Most environmental protection policies adopted by China focus on energy conservation and emissions reduction, and often require a trade-off between economic growth and environmental protection (Shen and Liu 2012).

Green innovation (GI), which means technological innovation related to environmental improvement, helps solve the dilemma. It simultaneously promotes economic growth and environment, that is, "green" economic growth (Wang et al. 2020; Li and Zhu 2019; Li et al. 2020). In recent years, China has paid increasing attention to the significance of GI as a means of achieving sustainable development. In 2015, the Chinese government put forward five development concepts, namely, "innovation," "coordination," "green," "openness," and "sharing," with the concepts of "green" and "innovation" attracting unprecedented attention. The Chinese government proposed the construction of a market-oriented GI system to encourage the development of clean production industries during the 19th National Congress of the Communist Party of China in 2017. In order to transform from "black" to "green" economic growth, China has taken a series of measurements to implement strict environmental regulation (Zhang et al. 2011).

This paper intends to study the effect of ER on GI by utilizing panel data from 30 provinces in China during the period 2002–2015 and a unique Chinese Patent Census Database. We contribute to the literature in three ways. First, in terms of the indicator of GI, this study, to the best of our knowledge, is the first to measure GI by taking into consideration both GI quantity and GI quality, which is attributed to our unique Chinese patent census data. Second, we find that while there is an inverted *U*-shaped relationship between ER and GI. However, the inverted *U*-shaped relationship occurred only in the eastern region, and regions with low pollution level, while the ER effects in other regions are insignificant. This indicates that the targeted policies should be made as to different regions. Third, we find that the positive effect of ER on GI is stronger for provinces with higher proportion of state-owned enterprises (SOEs), and thus disclose the special role of SOEs in promoting GI, which might be different from developed countries.

The remainder of this paper is organized as follows. Literature review section reviews the empirical studies of the impact of ER on GI. Model and data section introduces the data and regression model. Empirical results and discussion section presents baseline regressions and robustness tests. Heterogeneity section provides heterogeneity analysis. Conclusions and discussions are provided in Conclusions and discussions section.

## Literature review

There are pros and cons for enterprises as to the GI (Li et al. 2019a, 2019b) with diverse effects of the ER. Higher investments in pollution control are likely to squeeze out investment in GI. Enterprises may also embark on GI to reduce pollutions with new environmental technologies. Enterprises are more likely to invest in GI when the benefits of GI exceed the costs of complying with ER policies (Song et al. 2020).

The relationship between ER and innovation has been addressed in the literature. Some studies found a linear relationship: positive (Porter 1991; Porter and Linde 1995; Hamamoto 2006; Rubashkina et al. 2015; Zhang et al. 2020a), negative (Wagner 2007; Lanoie et al. 2008). No linear relationship was found by Jaffe and Palmer (1997) and Alpay et al. (2002). Other studies found a *U*-shaped relationship (Zhang et al. 2011; Shen and Liu 2012; Jiang et al. 2013).

There has also been research focusing on the relationship between ER and GI. Using data from various industrial sectors in China, Wang and Shen (2016) found an inverted *U*-shaped relationship between ER and GI (measured as environmental productivity). Using Xi'an (China) city as a case, Zhang et al. (2020b) also found an inverted *U*-shaped relationship between ER and GI efficiency, which is calculated based on directional distance functions. Wang et al. (2019) found an inverted *U*-

shaped relationship between ER and GI (measured as green productivity growth) in OECD (Organisation for Economic Co-operation and Development) countries. However, Song et al. (2020) found a *U*-shaped relationship between ER and GI, which is measured as the ratio of energy consumption and new product sales revenue of industries in each province. With data on Chinese listed companies, Cai et al. (2020) found a positive effect of ER on GI, measured as patent counts.

The extant studies have not been able to achieve consensus on the relationship between ER and GI. One of the reasons might be the different indicators for GI. Innovation indicators most commonly used in the literature are productivity, new product, research and development (R&D), and patent. When it comes to green innovation, productivity (Wang and Shen 2016; Wang et al. 2019), new product (Song et al. 2020), and patent (Cai et al. 2020) were used. However, Cai et al. (2020) only used the patent applications without considering patent quality. We take into account both the quantity and quality dimension of patents, and thus provide a more proper measurement of GI.

## Model and data

### Model

The industrial sector is the largest contributor to China's economic growth, but also the largest emitter of various kinds of pollution and the largest consumer of all forms of energy (Teng et al. 2019; Cheng et al. 2020). Thus, improvement in this sector's environmental performance is crucial for achieving "green" economic growth in China. Therefore, this study examined the impact of ER on GI using data from the industrial sector in 30 provinces in China during the period 2002–2015. The following model was used to estimate the effect of ER on GI:

$$Y_{\mathrm{it}} = \alpha_0 + \theta \mathrm{ER}_{\mathrm{it}} + \varphi \mathrm{ER}_{\mathrm{it}}^2 + \beta \mathrm{X}_{\mathrm{it}} + A_i + B_t + \varepsilon_{\mathrm{it}} \quad (1)$$

The logarithms of all variables were used to alleviate heteroscedasticity. The dependent variable $Y_{\mathrm{it}}$ denotes the level of GI in province *i* at time *t*, the independent variable $\mathrm{ER}_{\mathrm{it}}$ denotes the intensity of ER in province *i* at time *t*, and $X_{\mathrm{it}}$ is a set of control variables that may affect GI. Considering data availability, and based on previous related studies, we selected six control variables: GDP, firm size, SOE ratio, trade, pollution level, and foreign direct investment (FDI). To alleviate the possible endogeneity problem caused by missing variables, a two-way fixed-effects model was used wherein $A_i$ and $B_t$ denote the province fixed effects and the year fixed effects, respectively. $\alpha_0$ is the intercept term and $\varepsilon_{\mathrm{it}}$ is the error term.

## Variables and data

### Green innovation

Indicators for innovation include productivity, R&D, and patent. Previous studies on the impact of ER on GI have mainly used green productivity growth (Wang et al. 2019), environmental productivity (Wang and Shen 2016), and environmental R&D (Kneller and Manderson 2012) as proxy indicators for GI. However, none has analyzed GI from the perspective of patents. The number of Chinese patents granted has grown rapidly since the start of the 21st century, with data from the World Intellectual Property Organization (WIPO) indicating that the number of Chinese invention patents granted as a proportion of the global total has risen from 2.52% in 2000 to 30.37% in 2018. Patents have become an important measure of China's innovation boom, and more and more studies have used Chinese patent census data to study innovation-related issues (Wei et al. 2017; Cai et al. 2018).

The number of green invention patents in each province was taken as a proxy indicator of GI quantity in this paper. The WIPO classified all patents into 35 technology fields, one of which is "environmental technology" and that is the measure of green innovation in this paper. To a certain extent, the number of patents reflects the level of innovation; however, some low-quality patents may not represent real technological innovation, and as a result, the quality of patents also needs to be taken into serious consideration. While patent quantity of each province can be obtained from the *Patent Statistics Annual Reports* published by the State Intellectual Property Office of China (SIPO), patent quality is unavailable in these reports.

We utilized a unique Chinese Patent Census Database obtained from the SIPO, containing more than 22.12 million patents, to identify GI. The data is provided by TEKGLORY Co., Ltd. To the best of our knowledge, this is the first Chinese patent census data being updated to the year 2018 and containing abundant indicators related to patent quality. The Chinese patent census data used in existing studies, however, are up to 2014 at the latest (Wei et al. 2017; He et al. 2018; Cai et al. 2018).

The Chinese Patent Census Database includes many patent quality indicators such as the number of patent claims, which specifies the scope of protection of patent rights. Wider scope indicates higher quality of patents. The number of patent claims has been used to measure patent quality in many studies (Gilbert and Shapiro 1990; Bessen et al. 2008). Following Aghion et al. (2013), we obtained innovation quality by calculating the weighted patent quantity, with patent quality (the number of claims) as the weight.

### Environmental regulation and control variables

The proxy indicators for ER vary from study to study, but there are six main indicators: the operating costs of pollution control facilities (Rassier and Earnhart 2010), the ratio of pollution control costs to industrial output value (Wang et al. 2020), the number of inspections and supervisions of enterprises' emissions behavior (Brunnermeier and Cohen 2003), the amount of emissions such as waste gas, waste water, and solid waste (Domazlicky and Weber 2004), the ratio of GDP to energy consumption (Lanoie et al. 2008), and the ratio of pollution control investment to industrial output value (Gray 1987). Following Zhang et al. (2011), we used the ratio of pollution control investment to the output (value added) of industrial enterprises above a designated size as a measurement of ER.

The control variables were constructed as follows: (1) GDP per capita for each province was obtained from the National Bureau of Statistics (NBS) of China; (2) Firm size was obtained by taking the ratio of the total assets of industrial enterprises above a designated size to the number of industrial enterprises above a designated size in each province; (3) SOE ratio was obtained by taking the ratio of the total asset of SOEs to that of all industrial enterprises above a designated size; (4) Trade was obtained by taking the ratio of the total foreign trade value to the output (value added) of industrial enterprises above a designated size; (5) Pollution level was obtained by taking the ratio of the amount of sulfur dioxide emissions in the industrial sector to the output (value added) of industrial enterprises above a designated size; and (6) FDI was obtained by taking the ratio of FDI to the output (value added) of industrial enterprises above a designated size.

The data used to obtain these control variables are mainly taken from the China Easy Professional Superior (EPS) Database and the China Wind Database, with some supplementary data obtained from provincial statistical yearbooks. The nominal variables were all deflated with price indices taken from the NBS of China, using 2011 as the base year.

**Table 1** Descriptive statistics for the variables

| Variable | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|
| GI quantity | 0.0522 | 0.0706 | 0.0010 | 0.5443 |
| GI quality | 0.0525 | 0.2017 | 0.0000 | 1.7534 |
| GDP per capita | 1.3334 | 0.4568 | 0.4300 | 2.5056 |
| Firm size | 1.1497 | 0.4558 | 0.4524 | 2.5761 |
| SOE ratio | 0.4230 | 0.1239 | 0.1310 | 0.6448 |
| Trade | 6.8854 | 0.9335 | 5.2961 | 9.6227 |
| Pollution level | 5.3977 | 1.0739 | 2.0672 | 7.7675 |
| FDI | 4.4502 | 1.0225 | 0.0564 | 6.4349 |

Descriptive statistics are calculated using the logarithms of all variables

The province of Tibet was excluded from the analysis because of the large number of missing values. Table 1 displays the descriptive statistics for the variables used in this study.

## Empirical results and discussion

### Baseline specification

The regression results based on the abovementioned two-way fixed-effects model are shown in Table 2. Columns (1)–(3) and columns (4)–(6) show the results of the gradual addition of the province fixed effects and year fixed effects when taking GI quantity and GI quality as the dependent variable, respectively. Whether GI quantity or GI quality were taken as the dependent variable, the coefficients of ER and ER squared were positive and negative, respectively, at the 1% level of significance. This means that ER has a significantly positive effect on both GI quantity and GI quality when there is a low level of ER. However, as the intensity of ER increases beyond a certain point, it starts to have a negative effect on both GI quantity and GI quality. Thus, there is an inverted *U*-shaped relationship between ER and GI. This result is consistent with the results of Wang and Shen (2016), Wang et al. (2019), and Zhang et al. (2020a).

Among the control variables, GDP per capita negatively affects both GI quantity and GI quality, but this negative effect is significant only for GI quality. This finding of a negative effect of GDP per capita on GI confirms the findings of Zhu et al. (2019) and Wang et al. (2019). The coefficient of firm size is significantly positive, indicating that an expansion in the size of the enterprise promotes GI. SOE ratio has a positive effect on GI, in particular on GI quality, suggesting that the greater the proportion of SOEs, the stronger promotion effect of ER on GI. Trade has a significantly positive effect on GI quantity and GI quality, which might be caused by technology spillover or international competition. Pollution level has a significantly negative effect on GI quantity and GI quality, consistent with the finding of Wang et al. (2019). The reason would be that higher level of pollution requires more investment in pollution control, and thus is likely to crowd out investment in GI. FDI has a negative effect on GI quantity and GI quality, although this effect is insignificant after considering fixed effects, consistent with the finding of Hu et al. (2019).

### Robustness tests

#### Replacing the measurement of ER

To check whether the inverted *U*-shaped relationship between ER and GI is robust, we followed Zhang et al. (2011) in using the ratio of pollution control investment to overall operating

**Table 2** Baseline estimation results

| Independent variables | GI Quantity | | | GI Quality | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (1) | (2) | (3) |
| ER | 0.3658*** | 0.3724*** | 0.4220*** | 0.7316*** | 0.7745*** | 0.8766*** |
| | (0.1175) | (0.1148) | (0.1137) | (0.1664) | (0.1636) | (0.1669) |
| ER_squared | − 0.1794*** | − 0.1827*** | − 0.2071*** | − 0.3424*** | − 0.3488*** | − 0.4129*** |
| | (0.0572) | (0.0558) | (0.0553) | (0.0770) | (0.0757) | (0.0776) |
| GDP per capita | − 0.0118 | − 0.0184* | − 0.0201 | − 0.1414*** | − 0.1691*** | − 0.1538*** |
| | (0.0100) | (0.0102) | (0.0141) | (0.0325) | (0.0333) | (0.0467) |
| Firm size | 0.0359*** | 0.0414*** | 0.0461*** | 0.1218*** | 0.1422*** | 0.1831*** |
| | (0.0052) | (0.0054) | (0.0076) | (0.0169) | (0.0175) | (0.0252) |
| SOE ratio | 0.0544* | 0.0197 | 0.0082 | 0.3607*** | 0.2842*** | 0.2522*** |
| | (0.0287) | (0.0296) | (0.0335) | (0.0923) | (0.0955) | (0.1093) |
| Trade | 0.0151*** | 0.0071* | 0.0111** | 0.0304** | 0.0049 | 0.0105 |
| | (0.0039) | (0.0041) | (0.0045) | (0.0125) | (0.0135) | (0.0148) |
| Pollution level | − 0.0147*** | − 0.0133*** | − 0.0064 | − 0.0576*** | − 0.0566*** | − 0.0476*** |
| | (0.0043) | (0.0043) | (0.0048) | (0.0139) | (0.0141) | (0.0158) |
| FDI | − 0.0035*** | − 0.0032* | − 0.002 | − 0.0009 | − 0.0001 | 0.0014 |
| | (0.0018) | (0.0018) | (0.0019) | (0.0059) | (0.0059) | (0.0062) |
| Province fixed effects | No | Yes | Yes | No | Yes | Yes |
| Year fixed effects | No | No | Yes | No | No | Yes |
| N | 418 | 418 | 418 | 418 | 418 | 418 |
| $R^2$ | 0.4248 | 0.4316 | 0.4790 | 0.2876 | 0.2959 | 0.3349 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively

costs to measure ER, denoted as ER2. Table 3 shows the estimation results when ER2 is used as a proxy indicator for ER.

In Table 3, an inverted *U*-shaped relationship between ER and GI is still evident in terms of both GI quantity and GI quality. The results are consistent with those shown in Table 2, and confirms the robustness of our results.

### Eliminating the reverse causal effect

Kneller and Manderson (2012) and Rubashkina et al. (2015) pointed out that there might be a reverse causal relationship between ER and innovation, whereby innovation might affect the level of ER, which might lead to an underestimation of the role of ER. To alleviate the endogeneity problem and further refine the effect of ER on GI, we lagged ER by one period. The estimation results when taking ER_1 as an instrumental variable for ER are shown in Table 4. In Table 4, the coefficients of ER_1 and ER_1 squared are positive and negative, respectively, indicating an inverted *U*-shaped relationship between ER and GI, including both GI quantity and GI quality.

## Heterogeneity analysis

Previously, we analyzed the inverted *U*-shaped relationship between ER and GI. Now we come to the heterogeneity analysis in relation to the region, ownership structure, and pollution level, which might tell some new stories.

### Regional heterogeneity

There are large differences among provinces in China in terms of economic development, industrial structure, and ER

**Table 3** Robustness test 1: replacing the measurement of ER

| Independent variables | GI quantity | | | GI quality | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (1 | (2) | (3) |
| ER2 | 0.1421*** | 0.1461*** | 0.1786*** | 0.7316*** | 0.7445*** | 0.8776*** |
| | (0.0517) | (0.0505) | (0.0507) | (0.1664) | (0.1636) | (0.1669) |
| ER2_squared | − 0.0665*** | − 0.0686*** | − 0.0839*** | − 0.3424*** | − 0.3488*** | − 0.4129*** |
| | (0.0239) | (0.0234) | (0.0236) | (0.0770) | (0.0757) | (0.0776) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Province fixed effects | No | Yes | Yes | No | Yes | Yes |
| Year fixed effects | No | No | Yes | No | No | Yes |
| N | 418 | 418 | 418 | 418 | 418 | 418 |
| $R^2$ | 0.4187 | 0.4260 | 0.4746 | 0.2876 | 0.2959 | 0.3349 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively. The results for the control variables are not listed for the sake of simplicity

(Zhang et al. 2011). In this study, we divided the 30 provinces into three regions, namely, the eastern region, the central region, and the western region, to investigate the relationship between ER and GI in different regions. Table 5 shows the provinces in each region, while Table 6 displays the estimation results for each region. In the eastern region, the coefficients of ER are significantly positive, while those of ER squared are negative. These coefficients are insignificant in both the central and western regions. This suggests that there is an inverted *U*-shaped relationship between ER and GI in the eastern region, but no clear relationship in the central and western regions. Although ER does not have a significant effect on GI in the central and western regions, the signs of the coefficients of ER and ER squared suggest that there might be an inverted *U*-shaped relationship between ER and GI in the western region and a *U*-shaped relationship in the central region. Thus, the effects of ER on GI show different characteristics in the three regions.

One possible explanation for this is that enterprises in the eastern region produce lower levels of pollution than those in central and western regions, and thus there is no need for them to exert too much effort in relation to pollution control. Therefore, enterprises in the eastern region can invest more in innovation, especially GI, in response to the government's requirement of environmental improvement. In addition, the hardware and software infrastructures required for innovation are more mature in the eastern region than those in central and western regions. Therefore, the "anti-driving" effect of ER on GI is more evident in the eastern region than that in the central and western regions.

## Different ownerships

There are different types of ownership for firms in China, which might lead to different effects of ER on GI. In this study, the SOE ratio is measured by the ratio of the total assets of SOEs to

**Table 4** Robustness test 2: eliminating the reverse causal effect

| Independent variables | GI quantity | | | GI quality | | |
|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (1) | (2) | (3) |
| ER_1 | 0.2171* | 0.2109* | 0.2181* | 1.1563*** | 1.1356*** | 1.1586*** |
| | (0.1226) | (0.1195) | (0.1171) | (0.4012) | (0.3954) | (0.3928) |
| ER_1_squared | − 0.1058* | − 0.1029* | − 0.1077* | − 0.5674*** | − 0.5576*** | − 0.5748*** |
| | (0.0596) | (0.0582) | (0.0570) | (0.0362) | (0.1917) | (0.1912) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Province fixed effect | No | Yes | Yes | No | Yes | Yes |
| Year fixed effects | No | No | Yes | No | No | Yes |
| N | 390 | 390 | 390 | 390 | 390 | 390 |
| $R^2$ | 0.4064 | 0.4149 | 0.4668 | 0.2582 | 0.2677 | 0.3090 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively

**Table 5** Provinces in each region

| Regions | Provinces |
|---|---|
| Eastern | Beijing, Tianjin, Guangdong, Guangxi, Hebei, Jiangsu, Liaoning, Shandong, Shanghai, Fujian, Zhejiang, Hainan |
| Central | Shanxi, Inner Mongolia, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, Hunan |
| Western | Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang |

the total assets of industrial enterprises above a designated size. High SOE ratio refers to the group with SOE ratio higher than the average, and remaining observations are classified as low SOE ratio group. Table 7 shows the estimation results based on SOE ratio. In the high SOE ratio group, the coefficients of ER and ER squared are positive and negative, respectively, for both GI quantity and GI quality, and are both statistically significant at the 1% level, indicating an inverted *U*-shaped relationship between ER and GI. However, the coefficients are insignificant for the second group.

How should we interpret the finding that higher SOE ratio brings better promotion effect of ER on GI? In general, compared with non-SOEs, SOEs have a closer relationship with governments (Lin and Tan 1999), and are more willing to abide by government policies and regulations, resulting in better promotion effect of ER on GI. However, consistent with the above analysis, were the ER too strict on SOEs, it would have a negative effect on GI.

### Different pollution levels

The impact of ER on GI may vary with different levels of pollution. In this study, we used the ratio of the amount of sulfur dioxide emissions in the industrial sector to the output (value added) of industrial enterprises above a designated size to represent the pollution level. High pollution level group includes the provinces with pollution level higher than the average, and the remaining provinces are considered to be in the low pollution level group.

The results are shown in Table 8. ER does not have a significant effect on either GI quantity or GI quality in the high pollution level group, but an inverted *U*-shaped relationship is evident in the low pollution level group. The following examples help explain the findings. Hebei and Shanxi are two of the typical provinces with high pollution levels in China. On the one hand, most pollutions in the two provinces are from such industries as steel, cement, and coal, which have little to do with innovation (measured as patent). On the other hand, in order to meet the binding goals on environmental improvement in the 5-year plan, the central and local governments have to take some measures to control the relatively serious pollutions in a short time. The typical ways of controlling pollutions in the provinces with high pollution levels are stopping production or even shutting down the factories, rather than inventing new technologies for pollution control, which is time consuming. However, in provinces with low pollution levels, industries have more to do with innovation, and the task of pollution reduction is not that pressing. In fact, the results are in line with those for regional heterogeneity.

## Conclusions and discussions

GI is an important driving force for both environmental protection and economic growth. Using panel data from the

**Table 6** Regional heterogeneity

| Independent variables | The eastern region | | The central region | | The western region | |
|---|---|---|---|---|---|---|
| | GI Quantity | GI Quality | GI Quantity | GI Quality | GI Quantity | GI Quality |
| ER | 0.3258*** | 0.9410*** | − 0.1380 | − 0.0280 | 0.2326 | 0.1475 |
| | (0.0979) | (0.3202) | (0.0821) | (0.0460) | (0.2644) | (0.2037) |
| ER_squared | − 0.1648*** | − 0.4826*** | 0.0670 | 0.0137 | − 0.1144 | − 0.0727 |
| | (0.0459) | (0.1526) | (0.0399) | (0.0222) | (0.1296) | (0.0999) |
| Control variables | Yes | Yes | Yes | Yes | Yes | Yes |
| Province fixed effects | No | Yes | Yes | No | Yes | Yes |
| Year fixed effects | No | No | Yes | No | No | Yes |
| *N* | 154 | 154 | 126 | 126 | 124 | 124 |
| $R^2$ | 0.6849 | 0.5924 | 0.7071 | 0.6838 | 0.4960 | 0.3691 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively

**Table 7** Ownership structure heterogeneity

| Independent variables | High SOE ratio | | Low SOE ratio | |
|---|---|---|---|---|
| | GI quantity | GI quality | GI quantity | GI quality |
| ER | 0.6468*** | 2.8424*** | 0.1968 | 0.3944 |
| | (0.1481) | (0.5570) | (0.1499) | (0.2844) |
| ER_squared | − 0.3194*** | − 1.4020*** | − 0.0968 | − 0.1933 |
| | (0.0722) | (0.2714) | (0.0727) | (0.1380) |
| Control variables | Yes | Yes | Yes | Yes |
| Provincial fixed effects | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| *N* | 222 | 222 | 196 | 196 |
| $R^2$ | 0.5757 | 0.5160 | 0.6385 | 0.4989 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively.

industrial sector in 30 provinces in China during the period 2002–2015 and a unique Chinese Patent Census Database, this study analyzed the impact of ER on GI, and also the heterogeneous effects in terms of region, ownership structure, and pollution level.

The results suggest that there occurred an inverted *U*-shaped relationship between ER and GI in China. China has made ambitious commitments in terms of the Paris Agreement, and set a series of binding goals as to environmental improvement in the 5-year plan. In order to meet the above goals, the central government of China has carried out environmental supervisions and inspections more and more frequently. Accordingly, the local governments have set strict ERs for firms within their regions. However, too strict ER might hinder, rather than promote, GI, which is one of the most significant ways of reducing pollutions in the long term. Therefore, China should pay more attentions to the extent of ER. Furthermore, the effects of ER on GI differ greatly among regions. The inverted *U*-shaped relationship occurred only in the eastern region and provinces with low pollution level. This indicates that simply stopping production or shutting down factories might not be an effective way for reducing pollutions, especially in the middle and western regions, which are generally with high pollution level. Hence, China should also pay more attentions to the exact way of ER so that more GIs can be generated.

The inverted *U*-shaped relationship between ER and GI occurred only in provinces with high SOE ratio instead of provinces with low SOE ratio. SOEs are always criticized for their close relationship with the government, resulting in relatively low efficiency in generating profits. However, SOEs do have played a critical role in implementing environmental regulations, which can also be attributed to their close relationship with the government. Innovation activities are characterized by a long payback period, high levels of risk, and uncertain returns (Porter 1992) Therefore, government

**Table 8** Pollution level heterogeneity

| Independent variables | High pollution level | | Low pollution level | |
|---|---|---|---|---|
| | GI quantity | GI quality | GI quantity | GI quality |
| ER | 0.0367 | 0.1711 | 0.3529** | 1.0582** |
| | (0.2863) | (0.2409) | (0.1457) | (0.5132) |
| ER_squared | − 0.018 | − 0.0849 | − 0.1736** | − 0.5275** |
| | (0.1409) | (0.1186) | (0.0704) | (0.2480) |
| Control variables | Yes | Yes | Yes | Yes |
| Province fixed effects | Yes | Yes | Yes | Yes |
| Year fixed effects | Yes | Yes | Yes | Yes |
| *N* | 155 | 155 | 263 | 263 |
| $R^2$ | 0.5101 | 0.3286 | 0.6109 | 0.5313 |

Standard errors are shown in parentheses; ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively

intervention benefits SOEs in overcoming these uncertainties. But for non-SOEs to engage in GI under the ER, market incentives might be necessary.

It would be more accurate to study the impact of ER on GI at the micro level. However, we can only obtain provincial-level ER indicators, even though the patent data are available at the firm-level. This limitation may be rectified in future research once the data availability increases.

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**Availability of data and materials** The datasets generated and/or analyzed during the current study are not publicly available due to the confidentiality agreement of the patent data, but are available from the corresponding author on reasonable request.

## Compliance with ethical standards

**Competing interests** The authors declare that they have no competing interests

**Ethical approval** Not applicable

**Consent to participate** Not applicable

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