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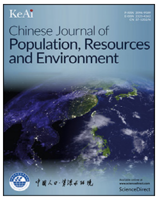

The impact of environmental regulation on total factor productivity of firms: An analysis based on technical distance

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ABSTRACT

Most studies on environmental policy and total factor productivity (TFP) growth under the heterogeneity framework tend to ignore the distance to the technical frontier, while research that investigates TFP growth based on technical distances does not tend to consider environmental policy. To fill this research gap, this study investigates the impact of environmental regulation on the total factor productivity of heterogeneous firms, based on technical distance. In addition to theoretical analysis, we apply a two-direction fixed effects model to test the impact using firm-level data selected from the CSMAR database and environmental regulation data of 287 Chinese cities between 2007 and 2015. We report two major findings from our analysis. First, environmental regulation increasingly enhances (or hinders) TFP growth, as firms get closer to (or further away from) the country-industry technology frontier, ceteris paribus. Second, grouped regression further highlights that environmental regulation affects TFP growth for heterogeneous firms. For proximal-type firms, environmental regulation promotes the growth of TFP through innovation and imitation mechanisms, while only the imitation mechanism works for middle-type firms. Neither mechanism, however, applies to distal-type firms, for whom environmental regulation hinders TFP growth. These conclusions provide a theoretical and practical basis for environmental policy, suggesting that the focus should be directed toward improving exit mechanisms for distal-type firms, creating a favorable market environment to accelerate the convergence of middle-type firms to the frontier, and encouraging proximal-type firms to innovate to catch up with or surpass the global frontier.

1. Introduction

After the 18th CPC National Congress, the central government of China began tightening environmental regulations and requirements, with the introduction of the new Environmental Protection Law in 2015 and the Thirteenth Five Year Plan for Ecological Environment Protection in 2016. In addition, all the province-level regions were covered by the central environmental protection supervision by 2017, and the aim of realizing Ecological Civilization and Beautiful China was added into the Constitution in 2018. More restrictive environmental regulation, however, would impose additional burden on firms, causing a shift in resources from production sectors to pollution abatement. It has been suggested that this could slow down the firm-level productivity growth, at least in the short run (Albrizio et al., 2017). However, supporters of the strong version of the Porter Hypothesis, argue that well-designed environmental policies also stimulate firms to innovate and thus increase productivity (Porter, 1991; Porter and Linde, 1995; Jaffe and Palmer, 1997). In China, one of the main objectives of environmental regulation is to establish a green and low-carbon economic system, in which firms are encouraged to transition from investment driven growth to innovation driven development. By doing so, it is expected that firms will focus on high quality development and improve their total factor productivity (TFP) growth. Nevertheless, firms are heterogeneous in nature, especially at the technology level; hence, they comply with environmental regulation in various ways. For example, some firms may be forced to exit and some may scale back production, while others may choose to imitate frontier technology or innovate independently. The different reactions to environmental regulation, as well as the different mechanisms that promote TFP growth, imply that not all firms will experience such growth. Thus, this paper aims to investigate the impact of environmental regulation on the TFP of heterogeneous firms. We particularly examine the mechanisms that promote TFP growth under environmental governance. Our findings add value to existing literature and have pertinent implications for policy makers.

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We categorize existing studies into three branches. The first branch examines the impact of environmental regulation on TFP under the assumption that firms are homogeneous. Several early studies have found that environmental regulation imposes an additional burden on firms by shifting resources from production and innovation, thereby lowering firm productivity (Gray, 1987; Jaffe and Stavin, 1995). Meanwhile, Porter (1991) and Porter and Linde (1995) propose that well-designed environmental instruments can stimulate firms to innovate. They argue that if the gain from innovation and the first-mover advantage can compensate for or exceed the compliance cost, there will be an increase in the firm's TFP. Jaffe and Palmer (1997) call this the strong version of Porter Hypothesis, which has been confirmed by several studies in China (see Li and Chen, 2013; Yuan and Xie, 2016; Guo et al., 2018). The relationship between environmental regulation and TFP does not have to be monotonic; previous research has found U-shaped, inverted U-shaped, and J-shaped correlations (Li et al., 2013; Shen, 2012; Han and Hu, 2015) as well. Such non-monotonic relationships are said to be a result of different policies or different levels of "stringency" in environmental regulation across regions (Zhang et al., 2011). Arguably, it may also be a result of heterogeneity among firms, which has been overlooked in these studies.

The second branch is related to the impact of environmental regulation on TFP under the assumption that firms are heterogeneous. Melitz (2003) provides new perspective and method to investigate the impact of environmental regulation. Under this framework, heterogeneous firms' reactions to environmental policies are reflected in their decisions on entry-and-exit, R&D investment, technical innovation, and emission reduction; thereby exhibiting different levels of TFP (Cui, 2017; Cao et al., 2016; Holladay, 2016; Rubashkina et al., 2015; Cohen and Tubb, 2018). Further analysis shows that the mechanisms of this phenomenon are related to the differences in firms' productivity, scale, ownership, emission, and location (Albrizio et al., 2017; Gray and Shadbegian, 2003; Huang et al., 2015). Notably, these studies do not tend to consider different technical distances of the firms from the frontier, which is an important factor in determining TFP growth.

The third branch deals with the relationship of the firm's TFP growth with technical distance to the frontier. Here, technical distance refers to the technological gap between a firm and the country-industry technology frontier. Following Aghion et al. (2001), several studies have investigated firms' TFP growths based on technical distance (Qiu et al., 2017; Bloom et al., 2013; Bas and Causa, 2013). Previous studies show that when firms are initially close to the technology frontier the increasing level of competition or the threat of new entrants will stimulate firms to innovate, in order to escape competition or the threat of new entrants. Firms further behind the frontier have no hope of winning against competition and thus will not innovate; in such cases the TFP growth will be hindered (Aghion et al., 2009). However, the firms lagging behind may promote TFP growth by imitating and absorbing the frontier technology; such catch-up effect is particularly evident for firms that are further away from the frontier (Bourles et al., 2013).

A research gap emerges from existing literature on this subject. Most studies on environmental policy and TFP growth under the heterogeneity framework tend to ignore the distance to technical frontier, while research that investigates TFP growth based on technical distances does not tend to consider environmental policy. Motivated by this dilemma, this paper examines the impact of environmental regulation on heterogeneous firms' TFP based on technical distance from a theoretical and an empirical perspective. The research results show that when firms get closer to (or further away from) the technology frontier, environmental regulation will increasingly improve (or hinder) TFP growth. We further study the underlying mechanisms by dividing firms into three groups: proximal-type, middle-type, and distal-type. For proximal-type firms, environmental regulation promotes TFP growth through innovation and imitation mechanisms; for middle-type firms, only an imitation mechanism works; and for distal-type firms, neither mechanism works in practicality. We believe that this research will contribute to the reassessment of the 'one-size-fits-all' environmental governance system in China, and provide the basis for recommendations to the government in the areas of green and sustainable development. This is particularly important because the country is undergoing a transitionary period from an investment-driven development mode to one that is driven by innovation.

The remainder of this paper is organized as follows. Section 2 explains the theoretical framework for the study, followed by the empirical analysis in Section 3. Further analysis and mechanism interpretations are presented in Section 4. The paper is concluded in Section 5, where we discuss policy implications and present our recommendations.

2. Theoretical framework

In the late 1980s, there was a breakthrough in classical growth theory. By assuming the endogenous technical progress, economists posited that economic growth could be endogenous. There are two kinds of endogenous economic growth models: one emphasizes that endogenous technical progress arises mainly from capital accumulation, while the other attributes endogenous technical progress to innovation. Such innovation can accelerate the exit of backward and obsolete products; this is the key point of the Schumpeter creative destruction theory. This economic growth model is therefore also called the Schumpeterian growth model (SGM). SGM assumes that TFP growth rate is influenced jointly by producer, consumer, and government. In this paper, the environmental regulation system also consists of government, producers, social organizations, and the common consumer, thereby exerting significant impact on TFP.

Following Aghion and Howitt (2006), we establish a firm's production function as:

$$Y = A_{ijt}^{1-\alpha} K_{ijt}^{\alpha} 0 < \alpha < 1 \tag{1}$$

where Y_{ijt} measures the output of firm i in industry j in year t. A_{ijt} is the greatest TFP achievable by firm i, using the most advanced technology in industry j in year t. K_{ijt} denotes a set of intermediate goods used in the production by firm i. In industry j, a successful innovator will replace its predecessor by increasing its technical parameter A, and will be sequentially replaced by the next successful innovator.

The technology frontier is defined as $\overline{A_{jt}}$, which plays an important role in promoting the incumbent's technical progress. On the one hand, it motivates advanced firms to increase R&D investment for cutting-edge innovation which, in turn, promotes the growth of technical parameter A_{ijt} by γ times and pushes to expand the technology frontier. On the other hand, it also encourages the lagging firms to imitate and adapt existing technology from the frontier. The decision for firms of whether to innovate or imitate depends on their respective technical distances to the country-industry technology frontier, but both mechanisms will tend to promote TFP growth.

Assuming that the probability for a firm to innovate or imitate is λ_{nijt} and λ_{mijt} respectively, the expected TFP growth of firm i in year $t+1$ is:

$$A_{ijt+1} = \lambda_{nijt}\gamma_{ijt}A_{ijt} + \lambda_{mijt}\delta_{ijt}\overline{A_{jt}} \tag{2}$$

where γ_{ijt} indicates the ability of firm i to improve TFP growth through innovation, while δ_{ijt} indicates the ability of firm i to improve TFP growth through imitation.

The change in TFP is therefore

$$\Delta A_{ijt} = \frac{A_{ijt+1} - A_{ijt}}{A_{ijt}} = \lambda_{nijt}\gamma_{ijt} + \lambda_{mijt}\delta_{ijt}\frac{\overline{A_{jt}}}{A_{ijt}} - 1 \tag{3}$$

where $\frac{\overline{A_{jt}}}{A_{ijt}}$ represents the technical distance of firm i to the industry technology frontier.

Equation (3) suggests that a change in technical distance may result in a change in TFP. The theory of the "advantage of backwardness" by

Gerschenkron (1962) suggests that lagging firms may catch up with the frontier in a short time by imitating and adopting existing technology. The further away a firm is from the frontier, the larger is the potential for this catch-up effect, the greater is the TFP growth, and the larger is λ_{mijt}. However, Matthews (1969) argues that the weaknesses in previous capital and knowledge accumulation may block a lagging firm's imitation, thereby hindering its TFP growth. Therefore, the net effect of technical distance on TFP must be empirically tested. Firms that are closer to the frontier are more likely to innovate as they have accumulated enough experience, capital, technology, and other resources to support innovation. Once they are successfully innovating, they will get the first-mover advantage and reap most of the benefits; thus λ_{nijt} is much larger for these firms. We summarize the above analysis in Proposition 1.

Proposition 1. As firms get closer to the frontier, they have an increasing preference to promote TFP growth by innovating. Conversely, as firms get farther away from the frontier, they are more likely to imitate, with the net effect of imitation on TFP growth depending on firms' absorption capacity.

The probability λ_{nijt} and λ_{mijt} in Equation (2) are influenced by various factors, such as environmental regulation. Let

$$\lambda_{nijt} = \alpha + \beta Z_{jt}\lambda_{mijt} = \eta + \mu Z_{jt} \tag{4}$$

where Z_{jt} measures the stringency of environmental regulation in industry j in year t. Combining Equation (4) with Equation (3), we get Equation (5):

$$\Delta A_{ijt} = \left(\alpha + \beta Z_{jt}\right)\gamma_{ijt} + \left(\eta + \mu Z_{jt}\right)\delta_{ijt}\frac{\overline{A_{jt}}}{A_{ijt}} - 1 \tag{5}$$

Taking the derivative on both sides of Equation (5) with respect to Z_{jt}, we have:

$$\frac{\partial \Delta A_{ijt}}{\partial Z_{jt}} = \beta\gamma_{ijt} + \mu\delta_{ijt}\frac{\overline{A_{jt}}}{A_{ijt}} \tag{6}$$

Equation (6) indicates that the impact of environmental regulation on TFP depends on the technical distance. Under the pressure of environmental regulation, firms that are close to the frontier face an innovation dilemma: on the one hand, environmental compliance cost reduces a firm's R&D investment, thereby weakening the firm's innovation capacity; on the other hand, firms may choose to innovate to avoid being eliminated from the competitive market (Aghion and Howitt, 2006). The first successful innovator gets the first-mover advantage and potentially the greatest TFP growth. Firms that are far away from the frontier are less capable of innovating, so they may exit if they cannot afford the compliance cost, or scale back production without any effort to promote technological progress that will hinder their TFP growth. Otherwise, they may imitate the existing frontier technology to make that progress in a short time. The benefits from imitation also partly offset compliance costs and promote TFP growth. Therefore, the sign for δ_{ijt} is ambiguous and needs support from empirical analysis.

Proposition 2. Under environmental regulation, as firms get closer to the frontier, they are more motivated to innovate and have greater TFP growth. As firms move further away from the frontier, they are less motivated to innovate, but the impact of environmental regulation on TFP is ambiguous, depending on their abilities to imitate frontier technology.

3. Empirical analysis

3.1. Empirical model

The primary objective of our empirical analysis is to identify the impact of environmental regulation on a firm's TFP, based on technical distance. In order to test the main propositions as described above, we construct the following regression:

$$\begin{aligned} lnTFP_{ijct} = {} & \beta_0 + \beta_1\frac{1}{3}\sum_{\lambda=0}^{2} REG_{ct-\lambda} + \beta_2 GAP_{ijt-1} + \beta_3\frac{1}{3}\sum_{\lambda=0}^{2} REG_{ct-\lambda}GAP_{ijt-1} \\ & + \beta_4 ln\overline{TFP}_{jt-1} + \beta_5 lnRD_{ijct} + \beta_6 Z_{ijct} + \eta_t + \alpha_j + \chi_c + \varepsilon_{ijct} \end{aligned} \tag{7}$$

where$TFP_{ijct}$is the TFP of firm$i$in industry$j$in city$c$in year$t$. REG_{ct} denotes the stringency of environment regulation in city$c$in year$t$. Since there may be a lagged effect for environmental regulation, we use a 3-year moving average ofREG_{ct} and $\lambda = 0 - 2$. GAP_{ijt-1} captures the technical distance of firm$i$to the country-industry technology frontier in the previous year. The coefficient β_2 is used to test Proposition 1, and the coefficient of the interaction term $REG_{ct} \times GAP_{ijt-1}$ is used to verify Proposition 2. $\overline{TFP}_{jt-1}$ is the technology frontier measured by the highest TFP across firms in industry$j$in year$t-1$. $lnRD_{ijct}$ represents the innovation capacity of firm$i$. Z_{ijct}includes a set of firm-level control variables, such as the firm's age, number of employees, sales revenue, ownership, government subsidy, asset-liability ratio, and Tobin Q index. $\eta_t\alpha_j\chi_c$, andε_{ijct}indicate the time-fixed effect, two-digit industry fixed effect, city-fixed effect, and the error term respectively.

3.2. Data

Unless otherwise stated, all our empirical data have been collected from the China Stock Market & Accounting Research Database (CSMAR). We use data from 2007 to 2015, because data on R&D investments of listed firms are only available from 2007. We focus only on the non-financial A-share companies listed in the Shanghai and Shenzhen stock markets. The CSMAR includes information at firm-level, such as the firm's name, stock code, industry code, date of establishment, operating revenue, amount of R&D investment, number of employees, government subsidy, ownership, etc. In the data cleaning process, we drop observations if: (i) one of the following variables has missing values: operating revenue, total assets, or net value of fixed assets; (ii) basic accounting principles are clearly violated, such as liquid assets exceed fixed assets, total fixed assets exceed total assets, and net value of fixed assets exceed total assets; (iii) the number of employees is smaller than 10; or (iv) the number of firms within an industry is less than 10. Furthermore, to avoid estimation bias caused by extreme values, we winsorize continuous observations at 1% and 99% levels for each year. The final sample for our analysis has 9038 observations. The main variables are defined as follows:

(1) TFP$lnTFP_{ijct}$. Various methods for calculating TFP have been mentioned in previous studies, but the OP (Olley and Pakes, 1996) and LP (Levinsohn and Petrin, 2003) methods are considered to be superior because of their suitability to ease endogenous, simultaneous, and sample selective problems. Using a firm's current investment as a proxy, the OP method calculates TFP in two steps. First, the proportion of labor in the production function and getting the coefficients for labor and capital is estimated. Second, by combining the two coefficients, the TFP can be estimated by applying the Solow residual method. The LP method is very similar, with the main difference being the use of intermediate inputs as a proxy to avoid problems such as negative investment variable. In this paper, we report the findings using the LP method, but we also use the OP and OLS methods to estimate the TFP to check for robustness.

(2) Environmental regulationREG_{ct}. Previous studies mainly use province-level data to describe the different levels of stringency of environmental regulation across regions (see Tu and Xiao, 2009; Yuan and Xie, 2016). This paper employs city-level data to allow more explicit control. The stringency of environmental regulation

is measured by the industrial sulfur dioxide (SO_2) removal rate in 287 prefecture-level cities, based on the assumption that the "stricter" the environmental policy, the higher is the removal rate. The original data for calculating SO_2 removal rate are collected from China City Statistical Yearbook from 2005 to 2015. To check for robustness, we also follow Ye et al. (2018) and construct a comprehensive indicator of environmental regulation, which consists of the removal rate of industrial SO_2 emission, attainment rate of industrial smoke and dust emission, and utilization rate of industrial solid waste.

(3) Technical distanceGAP_{ijt-1}. Similar to the work of Albrizio et al. (2017), we define technical distance as the distance to the country-industry frontier $GAP_{ijt-1} = ln\left(\frac{\overline{TFP}_{jt-1}}{TFP_{ijt-1}}\right)$, where$TFP_{ijt-1}$is the TFP of firm$i$in year$t-1$, and $\overline{TFP}_{jt-1}$is the technical frontier, defined as the highest TFP across firms by industry$j$in the previous year. A larger GAP_{ijt-1}implies that firm$i$is farther away from the technical frontier, and vice versa.

(4) Interaction term of environmental regulation and technical distance$REG_{ct} \times GAP_{ijt-1}$. The interaction term is used to test the heterogeneous effect of environmental regulation on a firm's TFP, based on technical distance. Theoretical analysis shows that technical distance plays an important role in the relationship between environmental regulation and TFP growth. When firms are far away from the frontier, environmental regulation may hinder their TFP growth, but when they are close to the frontier, environmental regulation may promote TFP growth. Hence, we expect a negative relationship between the interaction term and TFP growth.

(5) Innovation capability$\ln RD_{ijct}$. We use the ratio of R&D investment amount to the operating revenue to represent a firm's innovation capability. The ratio is taken in the logarithmic form. We expect innovation capability to be positively correlated with TFP growth, but innovation capability is also subject to technical distance. This means that the closer a firm is to the frontier, the stronger is its innovation capability and the higher is its TFP growth.

(6) Other control variables. We use the years of establishment to denote the firm's age$lnAge_{ijct}$, the number of employees by $lnNum_{ijct}$, and sales revenue by $lnSales_{ijct}$to represent firm's scale, and the ratio of fiscal subsidy to total revenue $lnSub_{ijct}$ to capture government intervention in the firm's compliance with environmental regulation. All these variables take the logarithmic form. The firm's ownership is a dummy variable: it is set to 1 if the largest part of a firm's paid-in capital is state-owned (SOE) or foreign-owned (FOE), and 0 otherwise. Asset-liability ratio $lnDAR_{ijct}$ is denoted by the natural log of total liabilities to total assets at the end of the period. The Tobin Q index$lnTQ_{ijct}$ is measured by the ratio of market value to the difference between total assets and intangible net assets, and also takes logarithmic form.

3.3. Estimation results

The Hausman test and auxiliary regression both show that the fixed effect mode is more suitable than random effect model and mixed regression model; we thus employ a two-way fixed effect model and the results of Equation (7) are listed in Table 1. From the Column (1) we find: (i) The coefficient of environmental regulation variable REG_{ct} is positive and highly significant at 1% confidence level, which confirms that environmental regulation improves the firm's TFP growth in general. (ii) The coefficient of $GAP_{ijt-1}$is negative and statistically significant at 1% level, implying that the further a firm moves from the technology frontier, the lower is the TFP growth. This result concurs with the work of Matthews (1969), who suggests that the lack of capital and knowledge accumulation may hinder the TFP growth of lagging firms. The negative coefficient also implies a higher TFP growth for a firm that is further away from the frontier. (iii) The interaction term also yields a negative and statistically significant coefficient, suggesting a counter-effect of technical distance on environmental regulation; while more strict environmental policies improve firms' TFP, the magnitude is reduced when firms move away from the frontier. For a firm that is far away from the frontier, the pressure to comply with environmental regulation is great, which crowds out innovation and hinders TFP growth. In contrast, when a firm gets close to the frontier, the benefit from innovation motivated by environmental regulation will exceed compliance cost, which finally promotes TFP growth as suggested by the strong version of the Porter Hypothesis. The findings provide preliminary evidence for Propositions 1 and 2; we find similar patterns when gradually adding variables, in Columns (2) and (3).

4. Robustness checks

We check the robustness of baseline estimation in three ways: (i) The industrial SO_2 removal rate is replaced with a comprehensive indicator to measure environmental regulation stringency. (ii) The OP method is used to calculate TFP as the dependent variable. (iii) We use the OLS method to estimate TFP as the dependent variable.

4.1. Comprehensive indicator of environmental regulation

Following Ye et al. (2018), we establish a comprehensive indicator of environmental regulation for 287 prefecture-level cities in three stages. First, we standardize the emission of various pollutants using Equation (8):

$$S_{i,j} = \frac{E_{i,j} - min(E_j)}{max(E_j) - min(E_j)} \tag{8}$$

where$E_{i,j}$is the emission of pollutant$j$in city$i$. There are three types of pollutants in our study: the removal rate of industrial SO_2 emission, the attainment rate of industrial smoke and dust emission, and the utilization rate of industrial solid waste. Raw emission data are collected from the China City Statistical Yearbook. $max(E_j)$ and$min(E_j)$ represent the maximum and minimum values of $E_{i,j}$ respectively. $S_{i,j}$ denotes the standardized emission.

Second, an adjustment coefficient for pollutant emission is calculated using Equation (9):

$$W_{i,j} = \frac{P_{i,j}}{O_i} \bigg/ \frac{\sum P_{i,j}}{\sum O_i} \tag{9}$$

where$P_{i,j}$denotes the emission amount of pollutant$j$in city$i$, and $\sum P_{i,j}$ represents the sum of all pollutants emission in city$i$. $O_i$and$\sum O_i$indicate the above scale industrial output value in city i and the sum of O_i in all cities, respectively.

Finally, we construct a comprehensive indicator using the following equation.

$$TR_i = \sum_{j=1}^{3} R_{i,j} \tag{10}$$

where$R_{i,j} = S_{i,j} \times W_{i,j}$, and it represents the indicator of environmental regulation of pollutant$j$in city$i$. TR_i denotes the comprehensive indicator of environmental regulation in city$i$. A higher value of TR_i means stricter environmental regulation in city i compared to others.

We use the comprehensive indicator as a proxy for environmental regulation to estimate Equation (7) again, and the estimation results are listed in Column (1) of Table 2. Although the magnitudes of coefficients have changed, as REG is measured by different methods, the signs and significance of key variables are consistent with those in Table 1, implying our baseline model is robust.

Table 1

The effect of environmental regulation on firm's TFP, based on technical distance.

	(1)	(2)	(3)
REG	0.7579***(0.0976)	0.2343***(0.0485)	0.1448***(0.0325)
GAP	−1.2142***(0.0404)	−2.0560***(0.0208)	−0.9377***(0.0184)
$REG \times GAP$	−0.2210***(0.0605)	−0.1129***(0.0300)	−0.1011***(0.0200)
$\ln\overline{TFP}$		0.5564***(0.0038)	0.2519***(0.0048)
$\ln RD$		0.0017***(0.0003)	0.0006***(0.0002)
$\ln Sales$			0.5515***(0.0062)
$\ln Num$			−0.1567***(0.0035)
$\ln TQ$			0.0044***(0.0005)
$\ln DAR$			−0.1218***(0.0108)
$\ln Sub$			0.0007 (0.0005)
$\ln Age$			−0.0021 (0.0022)
SOE			−0.0268**(0.0116)
FOE			0.0126 (0.0120)
Constant term	6.1009***(0.0650)	3.8902***(0.0357)	2.6828***(0.0746)
R^2	0.4506	0.8653	0.9437
Year-industry-city effects	YES	YES	YES
No. of Obs	9038	9038	9038

Notes: Figures in brackets denote the standard error. *Significant at 10%. **Significant at 5%. ***Significant at 1%.

4.2. OP method to calculate TFP

Column (2) in Table 2 shows the results of estimation where the dependent variable, that is, firm-level TFP, is calculated using the OP method. Thus, the results in Column (2) are consistent with Table 1, suggesting that the baseline estimation is robust.

4.3. OLS method to calculate TFP

The final robustness check uses the OLS method to calculate firm-level TFP, in accordance with previous studies, and adopts the calculations as a dependent variable to estimate Equation (7). The estimation results show some differences compared to earlier estimations but it does not change the sign and significance of most variables, which is consistent with baseline estimation. Details are presented in Column (3) of Table 2.

5. Further analysis: grouped regression based on technical distance

The theoretical and empirical analysis both show that the impact of environmental regulation on the firm's TFP largely depend on technical distance. When firms get closer to the frontier, environmental regulation stimulate more innovation, thereby leading to greater TFP growth. For firms that are further away from the frontier it is less possible to innovate, and imitation may be an easier way to improve TFP growth. The spillover effects from the frontier, however, depend on their absorption capability. To further study the estimation results above, we divide firms into three groups using the K-means clustering method based on their technical distances from the frontier and re-estimate Equation (7) by groups.

The clustering process includes three steps: first, the number of groups and initial cluster centers are defined; second, the Euclidean distance of every observation to every initial cluster center is calculated, and cluster centers are merged; third, the second step is repeated and the new cluster centers are re-clustered. This process is then iterated repeatedly until convergence is achieved. We divide the sample firms into three groups, according to their technical distance from the frontier: *proximal-type, middle-type, and distal-type*. Proximal-type refers to firms that are close to the frontier while distal-type are the firms that are further away from the frontier. Middle-type firms lie between the two. The key point of grouped regression is to test whether environmental regulation affects the firm's TFP growth through innovation mechanism. We thus interact the environmental regulation variable with the innovation variable, and include$\ln RD \times REG$ in Equation (7). The new regression equation is set as:

$$\ln TFP_{ijct} = \rho_0 + \rho_1 \frac{1}{3}\sum_{\lambda=0}^{2} REG_{ct-\lambda} + \rho_2 \ln RD_{ijct} + \rho_3 \ln RD_{ijct}\frac{1}{3}\sum_{\lambda=0}^{2} REG_{ct-\lambda} + \rho_4 \ln\overline{TFP}_{jt-1} + \rho_5 Z_{ijct} + \nu_t + \delta_j + \varphi_c + \mu_{ijct} \tag{11}$$

The estimation results for grouped regressions are listed in Table 3. First, for the *proximal type* firms, the coefficient of variable$\ln RD \times REG$ is positive and highly significant at 1% level, which means that environmental governance promotes TFP growth of these types of firms through innovation. The estimated result of the technical frontier variable $\ln\overline{TFP}$ is also significant and positive, suggesting that proximal type firms also promote TFP growth, through imitation mechanism. Second, for the middle-type firms in Column (2), the estimated result of $\ln RD \times REG$ is not statistically significant, which implies that induced innovation mechanism does not work here. But the coefficient of variableREG is significantly positive, hence environmental regulation is likely to improve the firm's TFP growth through imitation, since the estimated result of the technical distance variable is also significantly positive. Finally, for distal-type firms in Column (3), all the coefficients of the interaction term, environmental regulation variable, and technical distance variable are not significant, which means that environmental regulation would not improve TFP growth through innovation mechanism, nor through imitation.

6. Conclusion and policy implications

Based on the theoretical analysis of technical distance, this paper tests the impact of environmental regulation in 287 Chinese cities on TFP growth in firms, from 2007 to 2015. We focus on the listed firms selected from the CSMAR database. The conclusions are summarized as follows. (i) The results of both the theoretical analysis and the empirical suggest a heterogeneous relationship between environmental regulation and the firm's TFP growth, based on technical distance. When a firm gets closer to the technical distance, environmental regulation increasingly promotes the firm's TFP growth but the promotion effect gradually becomes weaker and even becomes negative when the firm moves away from the frontier. Robustness checks conducted in this study have confirmed this finding. Additionally, both R&D investment and technology spillover promote the firm's TFP growth. (ii) Grouped regressions further investigate the different mechanisms through which environmental regulation could affect firms' TFP growth. For proximal-type firms, environmental regulation promotes the growth of TFP through both innovation and imitation mechanisms. For middle-type firms, only imitation promotes the growth of TFP. Finally, the lack of absorption and innovation capacity means that environmental regulation neither stimulates TFP growth for distal-type firms through imitation, nor through innovation.

Table 2
Estimation results of robustness check.

		(2)	(3)
REG	0.0083***(0.0033)	0.0841***(0.0189)	0.1145***(0.0375)
GAP	−4.3091***(0.0404)	−1.7208***(0.0233)	−0.1694***(0.0045)
REG × *GAP*	−0.0311***(0.0084)	−0.2401***(0.0357)	−0.0210***(0.0061)
$\ln\overline{TFP}$	0.4492***(0.0045)	0.3929***(0.0036)	0.1982***(0.0030)
ln*RD*	0.0032**(0.0014)	0.0057*(0.0017)	0.0110**(0.0013)
ln*Sales*	0.3301***(0.0061)	0.0557***(0.0033)	0.0857***(0.0090)
ln *Num*	−0.0916***(0.0031)	−0.0291***(0.0033)	−0.1003***(0.0092)
ln *TQ*	0.0056***(0.0006)	−0.0001 (0.0004)	−0.0001 (0.0015)
ln *DAR*	−0.0013***(0.0004)	−0.0661*(0.0104)	−0.0900***(0.0321)
ln *Sub*	−0.0899***(0.0088)	0.0006 (0.0004)	−0.0041***(0.0015)
ln *Age*	−0.0002 (0.0016)	0.0046 (0.0021)	−0.0014 (0.0013)
SOE	−0.0172*(0.00960)	−0.0428*(0.0484)	−0.0563***(0.0187)
FOE	0.0067 (0.0098)	0.0153 (0.0500)	0.0106 (0.0331)
Constant term	2.019 8***(0.0190)	0.8563***(0.1233)	1.3162***(0.0514)
R^2	0.9610	0.8579	0.3507
Year-industry-city effects	YES	YES	YES
No. of Obs	8944	8944	8944

Notes: Figures in brackets denote the standard error. *Significant at 10%. **Significant at 5%. ***Significant at 1%.

Table 3
Regression results by groups based on technical distance.

	(1) proximal type	(2) middle type	(3) distal type
REG	0.1084**(0.0482)	0.1893***(0.0789)	0.0609 (0.0629)
ln*RD*	0.0132***(0.0034)	0.0082***(0.0013)	0.0384***(0.0121)
ln *RD* × *REG*	0.0133***(0.0049)	−0.0027 (0.0019)	0.0013 (0.0175)
$\ln\overline{TFP}$	0.1767***(0.0135)	0.2368***(0.0205)	0.0881 (0.0156)
Control variables	YES	YES	YES
Constant term	3.0574	3.6623	2.8333
R^2	0.2948	0.2906	0.2321
Year-industry-city effects	YES	YES	YES
No. of Obs	1616	3451	2655

Notes: Figures in brackets denote the standard error. *Significant at 10%. **Significant at 5%. ***Significant at 1%.

This study has valuable implications for policymakers and regulators. First, decision-makers should aim to strengthen environmental regulation and improve the exit mechanisms for low-tech firms. The results above show that environmental regulation is negatively correlated with distal-type firms' TFP growth, which also means that these firms were unable to adapt to the green development mode. Therefore, stricter environmental regulation measures, especially command-and-control instruments, should be applied to crowd out backward firms, and release resources to more efficient high-tech firms. Second, since environmental regulation may encourage middle-type firms to imitate and absorb frontier technologies, focus should be diverted to the improvement of the market environment to enable middle-type firms to catch up to the frontier. Market-based environmental regulatory instruments, such as fiscal subsidies, cannot be enhanced. Middle-type firms should also be encouraged to upgrade their status in the global value chain. Third, proximal-type firms are most creative, but they can easily be demotivated from innovating if their ideas and technologies are easily copied. Policymakers should therefore take measures to stimulate proximal-type firms to innovate; one way to do this would be to provide adequate protection of intellectual property rights. In addition, more market-based measures such as tax deduction should be enforced to encourage leading firms to innovate and catch up to, or even surpass, the frontier.

We recognize that there are a few shortcomings in this paper. There may have been a sample selection problem with our data as the CSMAR database only covers listed companies. Unlisted companies may behave and react to environmental regulation differently. We hope that this will be further investigated if data on these firms become available. Our environmental variable is not a direct measure of regulation, as it is proxied by SO_2 removal rate or a comprehensive indicator, which may be inversely affected by TFP growth. We leave the study of this reverse causality for future research.

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