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Original Article

Subnational institutions, firm capabilities and eco-innovation

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We examine the role institutional pressures, at the subnational level, play in the generation of eco-innovations and explicitly consider how they interact with firms' heterogeneous capabilities and ownership characteristics. Theoretically, we combine elements from institutional theory with the resource-based view of the firm to develop our hypotheses. Empirically, we use a novel dataset over the period 2003–2013 compiled from several sources: (I) environmental regulations (city-level) from the China Environmental Statistical Yearbooks and City Statistical Yearbooks; (II) green patents (firm-level) from the China National Intellectual Property Administration; and (III) ownership (firm-level) from the National Bureau of Statistics. Our econometric analysis employs an instrumental variable (IV) approach that controls for endogeneity and a negative binomial multilevel methodology for robustness. The results show that institutional pressures associated with environmental regulations, implemented at city level, lead to more green patents produced by firms in these jurisdictions. Crucially, the effectiveness of environmental regulation is enhanced when firms invest more in their internal technological capabilities. Finally, we find that a firm's affiliation with a business group enhances the positive effects of regulations in terms of the production of eco-innovations.

JEL classification: O31, O32, O33, Q53

1. Introduction

Escalating environmental concerns have heightened the imperative for both governments and corporations to address this daunting crisis (Krammer, 2024). Eco-innovations are new technologies developed to detect, measure, and tackle pollution, as well as minimize the environmental impact of products (Horbach *et al.*, 2012; Demirel and Kesidou, 2011; Barbieri *et al.*, 2016). Prior research on eco-innovation has focused on the effects of regulation on eco-innovations and a firm's economic performance, i.e., the "strong" and/or the "weak" Porter hypothesis (Kesidou and Demirel, 2012; Rexhäuser and Rammer, 2014; Zhang *et al.*, 2020), as well as on the various instruments of regulative frameworks (Fabrizi *et al.*, 2018). Yet, with some exceptions (Hering and Poncet, 2014), less attention has been given to institutional pressures at the level of cities (Liu *et al.*, 2020) despite their perennial prominence in the global economic landscape (Moomaw and Shatter, 1996). Here, building on institutional theory, we argue that owing to highly diverse institutional pressures across cities, environmental regulations at the city level—as opposed to the national level—might be more effective in driving sustainable development (Cole *et al.*, 2013;

Filiou *et al.*, 2023). This occurs because cities with strong institutional pressures can enhance firms' eco-innovation efforts as they strive to establish a strong sense of legitimacy.

Additionally, it is less well understood whether *all* firms are *equally capable* of complying with the various existing institutional pressures (Ghisetti and Pontoni, 2015). Building on the resource-based view (RBV) of the firm, we stress the role of heterogeneous technological resources and capabilities that enable firms to respond to regulation and produce green technologies. We argue that the effectiveness of institutional pressures depends on a firm's technological capabilities. This occurs because firms with high capabilities—i.e., proficient innovation departments and green-friendly human resource management (HRM) practices, etc.—can respond faster to regulation and change their innovation processes towards the generation of new knowledge that boosts green patents.

We test these predictions by examining the impact of two environmental regulations—those on sulfur dioxide (SO_2) removal rate and on environmental pollution abatement and control (PAC) expenditure—implemented in 285 cities in China. Additionally, we explicitly consider the moderating influence of firms' capabilities and ownership strategies on their propensity to produce eco-innovations. Our econometric analysis adopts a knowledge-production function (Grover, 2017), whereby the production of green patents is determined by city environmental regulation and firms' capabilities. We have generated a unique dataset by merging three different sets of data: (i) environmental regulation (city level), from the China Environmental Statistical Yearbooks and City Statistical Yearbooks; (ii) green patents (firm level) granted, from the China National Intellectual Property Administration (CNIPA); and (iii) the annual industrial enterprises survey (firm level), from the National Bureau of Statistics (NBS). We employ an instrumental variable (IV) approach and a negative binomial multilevel methodology.

Our results reveal that environmental regulation in cities and firm capabilities exert a positive impact on green patents. We also find that the effectiveness of environmental regulations increases when firms strengthen their internal capabilities through investments in research and development (R&D) or employee training. Finally, in line with our theoretical reasoning, affiliation with a business group (BG) enhances the effect of city-level environmental regulations on eco-innovations as proxied by the production of green patents.

This study contributes to the eco-innovation literature in two ways. First, prior research has predominantly focused on the impact of environmental regulations upon eco-innovations at the level of nation states, mainly due to the scarcity of data on regional or city regulations and their stringency (for a review, see Losacker *et al.*, 2023). In this article, drawing on insights from institutional theory, we demonstrate that diverse institutional pressures across cities have a significant impact on firms' eco-innovation activities. Our research complements earlier studies that account for the varied impact of national policies on the regional distribution of carbon emissions (Zhang *et al.*, 2021) and on industry-restructuring and labor markets, which may favor some regions and disadvantage others (Weller, 2012).

Second, building on RBV, we provide evidence of the key role firm-level capabilities and ownership choices play in enabling firms to respond to institutional pressures and take responsibility for the environment. Our findings align with recent scholarship highlighting the crucial roles of organizational capabilities (Figueiredo, 2003; Rauschmayer and Lessmann, 2013), ownership structures (Castellacci, 2015; García-Sánchez *et al.*, 2020), workforce skills (EEA, 2019; Marin and Vona, 2019), as well as the supporting institutional environments in stimulating innovation (Krammer, 2019; Rodríguez-Pose and Zhang, 2020; Chen *et al.*, 2021), particularly in the development of "green technologies" to curb pollution and reduce environmental externalities (Du *et al.*, 2019; Zhang *et al.*, 2020).

The paper is structured as follows. In Section 2, we develop three hypotheses using insights from institutional theory and the RBV, focusing on city environmental regulation, capabilities, and ownership choices, and their role in eco-innovation. Section 3 covers data and methodology, and Section 4 sets out the results of the econometric analysis. Finally, Section 5 presents the conclusions of this research and discusses its implications for academic and policy actors.

2. Theory and hypotheses

2.1 Institutional factors and eco-innovation

Institutional theory underscores legitimacy as the key driver affecting organizations' actions (Deephouse, 1996). Organizations conform with prevalent social norms and beliefs because they seek societal approval (Meyer and Rowan, 1977; DiMaggio and Powell, 1983). In turn, legitimacy concerns lead organizations to adopt homogeneous practices within an institutional jurisdiction, which breeds isomorphism. Scott (1995, 2005) emphasizes that organizational behavior can be attributed to regulatory and normative pressures. Regulation, especially state regulation, enacts formal rules and sanctions, which in turn exert pressure on organizations. "Normative pressures" refers to less stringent guidelines and social values that organizations seek to abide by.

The institutional environment has long been acknowledged to play a pivotal role in explaining a firm's environmental behavior, but more in environmental management than in eco-innovation. For instance, prior research has shown that strong institutional pressures are associated with the adoption of environmental standards, such as ISO 14001 (Delmas, 2002; Darnall and Edwards, 2006) and the substantive implementation of such standards (Boiral, 2007; Demirel *et al.*, 2018; Iatridis and Kesidou, 2018). Yet, with some exceptions (cf. Berrone *et al.*, 2013), less emphasis has been placed on the effects of institutional pressures on the environmental innovation activities of firms. Rather, previous research on eco-innovation has focused on the performance, competitiveness, or productivity effects of regulatory pressures. Porter and Van Der Linde (1995, p. 98) have argued that environmental regulations can drive innovation (i.e., "weak" version of Porter hypothesis) by partly offsetting compliance costs and increasing, in turn, firms' competitiveness (i.e., "strong" version of Porter hypothesis). The Porter hypothesis spurred a growth in research into eco-innovations (cf. Kemp and Pontoglio, 2011). They are often associated with higher productivity (Rexhäuser and Rammer, 2014) and higher profitability due to increasing consumer demand for green products and services (Rennings, 2000).

In contrast, our argument contends that institutional pressures have the capacity to influence a firm's eco-innovation activities, irrespective of their immediate profitability. This assertion aligns with prior research findings that demonstrate how institutional pressures drive family firms to improve their environmental performance practices, even when financial gains are lacking (Berrone *et al.*, 2010). In the next section, we delve into the specific mechanisms through which subnational institutional pressures, proxied by "city environmental regulations," influence a firm's eco-innovation activities.

2.1.1 City environmental regulation and eco-innovation

Environmental regulations are established by governments and are typically grounded on market failure rationales, such as environmental externality. The role of regulation is to induce firms to incorporate (internalize) the negative environmental externalities (i.e., pollution) of their industrial activities into their operations (Christainsen and Haveman, 1981; Gray, 1987). Firms adhere to these regulations as a means of safeguarding the legitimacy of their operations (Deephouse, 1996). Noncompliance can prove costly, with the imposition of penalties and sanctions that may even threaten the survival of a firm.

Prior research highlights the role of regulatory pressures in driving the adoption of environmental management standards (Darnall and Edwards, 2006). However, acceding to regulatory pressure through environmental management standards can sometimes result in a symbolic implementation of standards (Iatridis and Kesidou, 2018), primarily as a means to signal legitimacy to regulators (Darnall *et al.*, 2023). In contrast, eco-innovation represents a more proactive and substantial commitment to reducing pollution emissions (Horbach, 2008, 2014, 2016; Marzucchi and Montresor, 2017). Firms engaged in eco-innovation typically make costlier investments, with the potential for significant pollution reduction and the associated social benefits, including enhanced legitimacy (Berrone *et al.*, 2013). In the case of eco-innovation, government policies can address the "double externality problem" (Horbach *et al.*, 2012), which involves an environmental externality (as explained above) and an innovation externality. The second externality refers to the difficulty for a firm to fully appropriate the returns of its investments in eco-innovation.

This is because knowledge has attributes of a public good, and as such, other firms may make use of it without bearing the costs of the initial investment. Stringent regulations drive firms to invest in eco-innovations, as this enables them to improve their legitimacy, avoid costly penalties, and safeguard their reputation from potential damage (Kesidou and Demirel, 2012).

Yet, most of the past research has little to say on the *spatial* dimension of regulatory pressures and eco-innovation (Gibbs *et al.*, 2017). In recent years, policymakers and academics have shifted their attention to cities as the appropriate scale for implementing environmental regulations to combat climate change. For instance, the Organisation for Economic Co-operation and Development (OECD) focuses on policy frameworks in cities (e.g., Stockholm and Kitakyushu) where "green growth" is often reconciled with the pursuit of sustainable urban development (Hammer *et al.*, 2011; OECD, 2013).

A growing number of studies in economic geography show that the institutional configuration of environmental problems, and their solutions, may differ across space (Gibbs, 2006; Cooke, 2011, 2012; Truffer and Coenen, 2012; Horbach, 2014; Barbieri and Consoli, 2019). One strand of this literature suggests that the generation and/or specialization of green innovation varies across space due to regional spillovers (Antonioli *et al.*, 2016; Corradini, 2019) or because of the accumulation of different capabilities across regions (Balland *et al.*, 2015; Montresor and Quatraro, 2019; Antonioli *et al.*, 2022).

A different strand of the literature pays more attention to the variations in regulatory structures across regions, as the latter play a key role in coordinating the transition to new green regional paths (Cooke, 2012). Some recent studies—e.g., a patent data analysis on renewable technologies across regions in Italy (Corsatea, 2016) and a case study on waste management in Shanghai (Losacker and Liefner, 2020)—show that subnational administrative areas, such as regions or cities, with stringent environmental regulations induce greater rates of eco-innovation compared to cities with lax regulatory pressures (Cainelli *et al.*, 2015). Yet, there is scarce cross-sectoral quantitative evidence on whether environmental regulation leads to increasing rates of eco-innovation at the regional level, due to the limited availability of data on environmental regulations at the city or regional level.

Here, we contend that environmental regulations at the city level positively affect the generation of eco-innovations. As a result, we expect to observe an uneven distribution of green patents across cities, whereby cities with stronger environmental regulations are driving firms to increase their eco-innovations. Thus, our first hypothesis states:

> *H1: Stronger city environmental regulations will stimulate a firm's production of green patents.*

2.2 The role of resources and capabilities

Complementing institutional theory, which focuses on external factors that drive organizational behaviors and strategies, the RBV of the firm (Barney, 1991) provides powerful insights into its internal (or firm-specific) drivers. Specifically, RBV argues that the ability of firms to develop and sustain their competitive advantage is a result of unique (i.e., rare and difficult to imitate or substitute) bundles of resources. As such, a firm's capability to create or assemble these resources and bundles is intrinsically related to its performance vis-à-vis its competitors, and this includes also its innovation performance (Liu *et al.*, 2009; Terziovski, 2010). Building on these insights, we will argue that RBV-specific factors (i.e., internal capabilities and ownership characteristics) will also affect firms' performance in terms of eco-innovations.

2.2.1 Firm's internal capabilities and eco-innovation

Eco-innovations have the potential to spur firm competitiveness in two ways: first, by providing firms with a competitive advantage in terms of efficiency and reducing pollution (Salim *et al.*, 2019), and second, by distancing these eco-innovators from their non-innovating peers, which will be less likely to compete successfully in an environment where sustainability has become both a yardstick for success and a beacon for both governmental and consumer support.

The RBV approach has also played a key role in explaining technological change or innovation in firms, especially in the context of emerging economies. Specifically, evolutionary and structural economists have argued that innovation is the outcome of organizational investments in building technological capabilities (Lall, 1987; Figueiredo, 2003). "Technological capabilities" (i.e., the ability of a firm to generate and manage technical change) denotes the capacity to search for an appropriate technology, compare it to alternative technologies, select a new technology, install, adapt, and/or modify the new technology, and generate a new technology (Bell and Pavitt, 1993). Prior studies have consequently made a compelling case that technological capabilities are among the drivers of eco-innovations (Ghisetti and Pontoni, 2015; Marzucchi and Montresor, 2017; Demirel and Kesidou, 2019; Dai *et al*., 2020).

In addition to technological prowess, the ability of organizations to secure and engage high-quality human capital is a crucial asset in the development of innovations. In particular, the role of tailored HRM practices like performance-based incentives and job autonomy has been linked to superior organizational innovative outcomes (Krammer, 2022). Similarly, "green" HRM practices can help organizations better align their business strategies with existing environmental needs. Practices like green hiring, training, appraisal, and incentivization of employees have therefore all been linked to positive effects on sustainability (Yong *et al*., 2020), reinforcing the secular trend of skill upgrading triggered by globalization (Marin and Vona, 2019). In addition, such pro-environmental organizational capabilities can also stimulate the development of a green organizational culture, which will further propagate a firm's emphasis on and interest in developing eco-innovations through channels such as leadership emphasis, peer involvement, and employee empowerment (Roscoe *et al*., 2019).

To sum up, we believe that both technological and organizational capabilities (such as HRM practices) will positively affect the ability of firms to develop eco-innovations. Consequently, our second hypothesis states:

> *H2a: Stronger internal capabilities will stimulate a firm's production of green patents.*

Further to the direct effects of internal capabilities, we suggest that they will also have indirect effects on a firm's eco-innovation by influencing the effectiveness of regulatory push at the level of the city. This conceptualization implies that firms failing to comply fully with extant regulations are not necessarily acting irresponsibly. This is especially the case with small and medium enterprises (SMEs), which often have scarce resources and information (Love and Roper, 2015). For example, it is quite likely that firms might not have the capabilities to compare alternative green technologies to reduce their carbon emissions. Qualitative evidence from the UK indicates that compliance with environmental regulations differs across SMEs due to their heterogeneous resources and capabilities (Lynch-Wood and Williamson, 2014). A recent study from China suggests that firm heterogeneity moderates the relationship between a firm's compliance with environmental regulations and that firm's pollution emissions (Pang *et al*., 2022).

Building on the preceding discussion, this article posits that organizational capabilities will moderate the relationship between regulation and eco-innovation. Firms with high capabilities (i.e., proficient innovation departments, green culture, green-friendly HRM practices, etc.) can respond faster to regulation and change their innovation processes towards the generation of new knowledge that boosts green patents. Thus, we propose:

> *H2b: Stronger internal capabilities will positively moderate (i.e., strengthen) the relationship between city environmental regulation and a firm's production of green patents.*

2.2.2 Ownership capabilities and eco-innovation

In addition to the effects of internal capabilities discussed in the paragraphs above, we contend that a firm's willingness and ability to engage in eco-innovation are also shaped *indirectly* by its ownership structure, which can also be considered a reflection of the firm's own capabilities (He *et al*., 2016). Specifically, we focus on firms' affiliation to BGs (Guillen, 2000), which may generate several benefits for affiliated firms as opposed to independent ones (Carney *et al.*, 2011). Our intuition is motivated by two rationales around willingness and expected benefits, as follows.

Firstly, the willingness of an affiliate to engage in eco-innovation will be greater for a firm affiliated with a BG than for one that is not due to within-group spillovers, diversification benefits, and better access to (financial and nonfinancial) resources within a group. An affiliated firm is more likely to engage in eco-innovation driven by expertise and engagements from other members of the group than motivated solely by the mandate of its individual stakeholders (Khanna and Yafeh, 2007). Therefore, we would expect, on average, affiliates to be more likely to undertake environmentally responsible initiatives (e.g., eco-innovation) than independent firms (Choi *et al.*, 2018). Second, BGs benefit from significant products and international diversity, which in turn may provide a hedge against the costs and risks of eco-innovation, should it be unsuccessful in a particular context (i.e., country or industry) (Yiu *et al.*, 2005). Third, BG affiliates will have more opportunities of accessing the much-needed financial resources mandates through a long-term, radical, and risky activity such as eco-innovation. This financial flexibility confers on them a better ability to capitalize on their existing capabilities and pursue this type of innovation, as compared to individual firms. Likewise, BG affiliates will likely benefit more from better dynamic capabilities and opportunities, given their ability to share technologies and know-how across group members (Castellacci, 2015), which will further increase their propensity to develop eco-innovations.

Our second rationale is driven largely by reputational effects, which tend to be much more prominent for BG-affiliated firms than for standalone ones. In turn, such reputational effects will make BG affiliates more sensitive to institutional pressure, and thereby more likely to produce green patents. The existing literature has documented the significant and group-wide effect of reputational externalities for BG affiliates (Cuervo-Cazurra, 2018). Particularly with respect to negative events related to environmental scandals (e.g., hidden pollution, accidents, or negligence), reputational capital is likely to be damaged for all affiliates of the group. In such instances, investing in corporate social responsibility and environmental activities can serve as a strategic hedging option or a buffer to maintain the reputation of group members (Choi *et al.*, 2018), in contrast to its usefulness for standalone firms. Considering all these arguments, we would expect the group affiliation of a firm to serve as a catalyst for that firm's internal capabilities, enabling it to respond to environmental regulations, and in turn encourage more eco-innovation.

Building on these core rationales we propose:

> *H3: Affiliation to a business group (BG) will positively moderate the relationship between city environmental regulation and a firm's production of green patents.*

3. Methodology

3.1 The evolution of pollution and institutional pressures in China

Prior to economic reforms and the opening of the Chinese economy, environmental issues were not a government priority. Figure 1 depicts the evolution of carbon emissions in China from 1970 to 2020. Carbon emissions in China have increased by more than 1300% over the past 50 years, from about 7,70,000 kilotons in 1970 to more than 10 million kilotons in 2020. The Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution was enacted in 1987, introducing comprehensive controls for air pollution. The average annual growth rate of carbon emissions was 5.1% from 1970 to 2000, but accelerated to 9.8% from 2001 to 2010 during the rapid industrialization of China's economy. This prompted the Chinese government to revise the law in 1995, 2000, and 2015, leading to stricter environmental measures and increased penalties for environmental violations (Zhang *et al.*, 2022). As a result, China's carbon emissions showed a decline between 2014 and 2016 (Figure 1). However, emissions began to increase after 2016 (Figure 1), a trend possibly attributable to a decrease in the stringency of environmental policies (Zhang *et al.*, 2022, p.4–5).

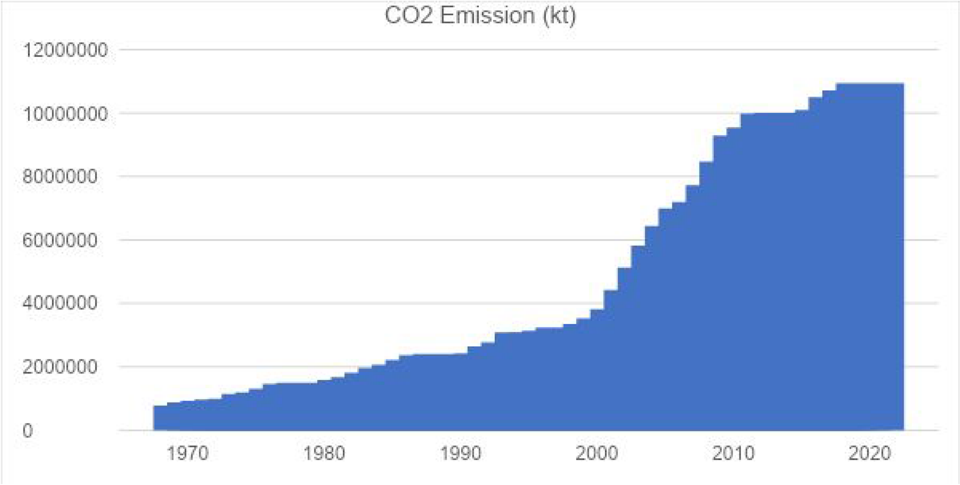

Figure 1. The evolution of carbon emissions in China. Data source: CSMAR (https://www.gtarsc.com).

3.2 Data

We have created an original dataset by merging three distinct datasets as follows. First, we measured firm-level eco-innovation over the period 2003–2013 using *green* patents. Patent data were collected from the database of China's National Intellectual Property Administration (CNIPA), formerly China's State Intellectual Property Office (SIPO). The database contains detailed information on patents (Dang and Motohashi, 2015), including application number, application date, International Patent Classification (IPC), patent type (invention, utility model, or appearance design), applicants' names and addresses, inventors' names, and patent attorneys' names and addresses. China formally enacted the Patent Law in 1984, and it came into force in 1985. Until the end of the 1990s, the number of patent applications by residents grew modestly at an average annual rate of 11%. However, since the turn of the century, the number has surged dramatically, with an average growth rate of 30%, reaching 5,243,592 in 2021,[1] according to the World Intellectual Property Organization (WIPO). CNIPA database offers the most detailed and comprehensive coverage of Chinese domestic patents (Choi, 2011) and has been widely used in existing studies including those published in leading journals (e.g., Hu *et al*., 2017; Christodoulou *et al*., 2018; Tong *et al*., 2018; Huang *et al*., 2021; Wu *et al*., 2021; Zhu *et al*., 2022; Wang *et al*., 2023; Yan *et al*., 2024).

Second, we measured the city-level environmental regulations of 285 cities over the period 2003–2013 using data we obtained from the China City Statistical Yearbooks and China Environmental Statistical Yearbooks. Following prior studies (Lanjouw and Mody, 1996; Jaffe and Palmer, 1997; Popp, 2006), we used two proxies to capture the stringency of city environmental regulation: (i) *industrial sulfur dioxide removal rate* (SO_2); and (ii) *city environmental PAC expenditure*.

Third, we used the Annual Industrial Enterprises Survey (AIES) dataset from the National Bureau of Statistics (NBS), which lists firms that had an annual turnover of more than RMB 5 million during the period 2003–2013. It includes detailed information on firms, such as *R&D, training, ownership, location, industry, assets, revenue, investment, profit, export, employment, and cash flow*. Firms' distribution across the cities and the cities' energy consumption are shown in Appendix A. The table indicates that firms are relatively evenly distributed across cities in China, which demonstrates that the dataset does not have a serious regional bias. Due to entry and exit, and to ownership restructuring, the number of firms in operation changes over time. The data were cleaned via extensive checks for nonsense observations, outliers, coding mistakes,

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[1] https://www3.wipo.int/ipstats/

and similar measurement errors. We dropped all observations that had missing values for key financial variables (such as total assets, fixed assets, and industrial output) or when the number of employees was reported to be less than 10. This finally produced an unbalanced panel dataset.

3.3. Variables

3.3.1 Eco-innovation

We measure eco-innovation using patent data in line with previous research (Jaffe and Palmer, 1997; Wagner, 2007; Johnstone *et al.*, 2010; Oltra *et al.*, 2010). Green patents are inventions, utility models, and appearance designs associated with environmental technologies that can improve energy efficiency, reduce air pollution, and achieve sustainable development. They range from alternative energy, environmental protection materials, and energy conservation to emissions reduction, pollution control, and recycling technologies.[2] To identify green patents, we follow the latest guidelines combining the OECD methodology (ENV-TECH) (Haščič and Migotto, 2015) and the WIPO methodology (IPC Green Inventory)[3] (Favot *et al.*, 2023).

3.3.2 Environmental regulations

Prior work by environmental economists has revealed that environmental regulations are *essential* determinants of eco-innovations (Rothfels, 2002; Hart, 2004; Popp, 2005). In line with previous research, we measure the stringency of environmental regulation across cities using the *industrial sulfur dioxide removal rate* (SO_2) (Gollop and Roberts, 1983; Javorcik and Wei, 2001). This is a command-and-control instrument, which refers to legislation and rules that set specific targets and standards, where compliance is mandatory (Jaffe and Palmer, 1997; Kesidou and Wu, 2020).

We also measure the stringency of environmental regulation using *city-level PAC expenditure*. PAC expenditure is an imperfect proxy of environmental regulation. It has been used extensively in prior research because it allows researchers to capture the changes in opportunity costs of the use of environmental resources (e.g., changes in the relative input prices) that occur when regulation becomes stringent (Jaffe *et al.*, 1995; Brunnermeier and Cohen, 2003). The premise is that public expenditures that reduce environmental impact can increase the efficiency of other factors of production and firms' incentives to improve production technology. This, in turn, improves firms' productivity and technological innovation (Lanjouw and Mody, 1996; Jaffe and Palmer, 1997; Popp, 2006). Here, *city-level PAC expenditure* measures the total expenditure in city environmental protection and pollution control infrastructure related to environmental law enforcement costs, environmental personnel input, and environmental capital expenditures.

3.3.3 Firm capabilities

Building internal technological and human capabilities is seen as driving eco-innovation (Horbach *et al.*, 2012; Triguero *et al.*, 2013). Prior studies have predominantly stressed the role of technology push factors for eco-innovation (Canon-De-Francia *et al.*, 2007; Costantini *et al.*, 2015; Demirel and Kesidou, 2019). We use *R&D investment* (*R&D*) and *employee training expenditure* (*TRAIN*) to measure technological and human capabilities, respectively.

3.3.4 Business group affiliation

A commonly accepted definition by Khanna and Rivkin (2001) describes a BG as "a set of firms which, though legally independent, are bound together by a constellation of formal and informal ties and are accustomed to taking coordinated action" (p. 47). BGs are prevalent in both developed and emerging economies and remain the dominant form of firms in emerging economies as a response to institutional voids (Yiu *et al.*, 2005; Khanna and Yafeh, 2007; Yaprak and Karademir, 2010; Carney *et al.*, 2011; Holmes *et al.*, 2018). We measure BG affiliation to equal 1 if a firm is affiliated with a BG and 0 otherwise.

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[2] China National Intellectual Property Administration (CNIPA).

[3] http://www.wipo.int/classifications/ipc/en/green_inventory/

Table 1. Definition and descriptive statistics of main variables

Index code	Variable/level	Definition	Mean	Std. Dev.
Eco	Eco-innovation (firm-level)	Green patents granted to each firm	0.014	0.140
Ecop	Eco-innovation proportion (firm-level)	Green patents granted to each firm scaled by total patents	0.006	0.065
SO_2	SO_2 removal rate (city-level)	Industrial sulphur dioxide removal volume/Industrial sulphur dioxide production volume (unit: ton)[a]	0.444	0.238
PAC	Pollution Abatement and Control expenditures (city-level)	City environmental pollution abatement and control expenditures (unit: 10,000 yuan; logarithm)	15.938	1.752
R&D	Research and Development (firm-level)	R&D (unit: 1000 yuan; logarithm)	0.669	2.021
TRAIN	Employees training expenditure (firm-level)	Employees training expenditure (unit: 1000 yuan; logarithm)	1.767	2.054
BG	Business group (firm-level)	Business group (dummy variable)	0.008	0.088
SIZE	Firm size (firm-level)	Firm size (measured by total assets, unit: 1000 yuan; logarithm)	10.198	1.500
PROFIT	Profitability (firm-level)	Profit per employee (unit: 1000 yuan)	37.074	83.511
WAGE	Wage (firm-level)	Wage per employee (unit: 1000 yuan)	21.084	26.051
FOREIGN	Foreign ownership (firm-level)	Foreign-invested firms (dummy variable)	0.115	0.319
ENERGY_CONS	Demand pull (city-level)	Energy consumption/ total population (unit: 10,000 tons of standard coal)	40.816	34.313

[a] Industrial sulfur dioxide production volume = Industrial sulfur dioxide removal volume + Industrial sulfur dioxide emissions volume.

3.3.5 Control variables

We control for a series of factors that might affect firms' eco-innovation. First, we use total assets to proxy for the *size of the firm* (*SIZE*). Second, since better-performing firms are more likely to pursue environmental goals (Nakamura *et al.*, 2001), we control for profitability, using *profit per employee* (*PROFIT*), and for the wage level, which is captured by *wage per employee* (*WAGE*). Third, we control for *foreign ownership* with a dummy (*FOREIGN*), as foreign direct investment has long been regarded as bringing advanced technology and managerial knowledge. Multinational enterprises (MNEs) and their affiliates are an important force conducting cutting-edge research and innovation, and are often regarded as possessing certain competitive advantages that enable them to succeed in the international market. Finally, we further consider a city-level energy demand pull by using *energy consumption per capita* (*ENERGY_CONS*).

Table 1 provides the variable definition, measurement, and summary statistics. The correlation coefficients for all variables are shown in Table 2. Correlation coefficients are low. The variance inflation factors (VIFs) range from 1.13 to 2.89, well below the threshold level of 10.

Table 2. Correlation matrix

	Eco	Ecop	SO_2	PAC	R&D	TRAIN	BG	SIZE	PROFIT	WAGE	ENERGY_CONS
SO_2	0.005	0.008									
PAC	0.020	0.025	0.266								
R&D	0.138	0.114	0.013	0.029							
TRAIN	0.070	0.064	0.019	0.016	0.348						
BG	0.036	0.012	0.007	0.071	0.101	0.099					
SIZE	0.105	0.085	0.005	0.055	0.352	0.407	0.099				
PROFIT	0.003	0.031	0.0004	0.003	0.010	0.014	0.407	0.049			
WAGE	0.050	0.041	0.049	0.144	0.143	0.137	0.014	0.253	0.114		
ENERGY_CONS	0.002	0.020	–0.125	–0.278	–0.004	0.002	0.137	0.073	0.010	–0.003	
FOREIGN	0.011	0.022	0.036	0.158	0.046	0.027	0.002	0.193	0.014	0.175	–0.017

3.4. Empirical model

To examine the eco-innovation and environmental regulation relationship, the basic econometric model is as follows:

$$Eco-innovation_{it} = \beta_0 ER_{ct-2} + \beta_1 C_{it-2} + \beta_2 ER_{ct-2} * C_{it-2} + \gamma_i X_{it-2} + T_t + F_i + \varepsilon_{it} \qquad (1)$$

where *Eco-innovation* $_{it}$ denotes green patents granted to firm *i* in year *t*. *Eco-innovation*$_{it}$ is measured in two ways for robustness: (i) total number of green patents granted to firm *i* in year *t (Eco)* and (ii) share of green patents as a percentage of total patents granted to firm *i* in year *t (Ecop)*.

The two main explanatory variables are: *ER* (Environmental Regulations: SO_2 and *PAC*) set in city *c* in year *t*. *C* (Capabilities—technological *R&D* and human *TRAIN*). $X_{it\text{-}2}$ is a vector of control variables. F_i is firm fixed effects (including *BG*), T_t is year fixed effects, ε_{it} is the error term. In line with prior research, we lagged all the explanatory variables by 2 years (Krammer, 2009).[4]

Our objective is to estimate the effects of environmental regulations in the context of cities on the generation of eco-innovations, by considering firms' heterogeneous capabilities and ownership characteristics. To mitigate the concerns of reverse causality between eco-innovation and environmental regulations and possible confounding factors, we adopt the following strategies.

First, we include firm-level control variables that are often considered to impact on eco-innovations: *SIZE* (Scarpellini *et al.*, 2018; García-Sánchez *et al.*, 2020), *PROFIT* (You *et al.*, 2019), *WAGE* (Ni and Kurita, 2020), and *FOREIGN* (Peñasco *et al.*, 2017). Second, we include fixed effects to absorb time-invariant unobserved heterogeneity—e.g., unobservable changes in the firm's operating environment or in the business cycle—that may be correlated with strategic decisions on eco-innovations.

Third, we employ a widely used IV of environmental regulation, namely, ventilation coefficient (Broner *et al.*, 2012; Hering and Poncet, 2014). This is because environmental regulation might be endogenously determined due to the geography of a city. The ventilation coefficient is calculated using the product of wind speed and the mixing height for each city. We employ the wind speed information at the height of 10 m and the boundary layer height (Shi and Xu, 2018). This is because there are two meteorological factors that determine the diffusion of pollutants: (i) wind speed, where a faster wind speed is conducive to the horizontal diffusion of pollutants; and (ii) mixed layer height, which reflects the vertical dispersion of pollutants (Jacobson, 2002). Hence, the ventilation coefficient is negatively correlated with the environmental regulation stringency. We collected this data information from the European Centre for Medium-Range Weather Forecasts ERA-Interim dataset. Subsequently, we merged the ERA-Interim data with each city by its latitude and longitude. To check the validity of IVs, we report the Kleibergen-Paap LM statistics and the Kleibergen-Paap F statistics. These tests give us confidence in the results of our IV estimation.[5]

Fourth, for the robustness check, we report negative binomial multilevel analysis results. Negative binomial multilevel regression is an appropriate econometric technique to model count data (i.e., discrete number of occurrences of an event in a fixed period of time). A count variable, such as granted patents, can take positive integer values or zero. Poisson regression analysis is often used to model count data. The negative binomial model is selected to model over dispersed count data for which the variance is greater than that of a Poisson model (as it is in our case). In a Poisson model, the variance is equal to the mean, and thus overdispersion is defined as the extra variability compared with the mean (Gardner *et al.*, 1995; Cameron and Trivedi, 1998).

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[4] The results are robust with respect to changes in the time lag (1 year or 3 years) of the regressors.

[5] Since we have one IV, we don't test both environmental regulation stringency proxies simultaneously.

Table 3. Environmental regulations, capabilities (R&D), and eco-innovation: two-stage least square estimations

Dependent variable: Eco[a]	(1)	(2)	(3)	(4)
SO_2	0.027*		0.024*	
	(0.014)		(0.015)	
PAC		0.255***		0.250***
		(0.072)		(0.070)
SO_2*R&D			0.019***	
			(0.002)	
PAC*R&D				0.010***
				(0.003)
R&D	0.004*	0.003	0.010***	0.007***
	(0.002)	(0.002)	(0.002)	(0.003)
SIZE	0.012	0.011	0.012	0.010
	(0.010)	(0.012)	(0.010)	(0.012)
PROFIT	0.088***	0.078***	0.088***	0.078***
	(0.016)	(0.018)	(0.016)	(0.018)
WAGE	0.169	0.156	0.164	0.144
	(0.127)	(0.165)	(0.127)	(0.163)
FOREIGN	0.010	0.004	0.010	0.005
	(0.007)	(0.007)	(0.007)	(0.007)
ENERGY_CONS	0.009	0.005	0.013	0.006
	(0.020)	(0.015)	(0.020)	(0.015)
observations	259,935	251,885	259,935	251,885
Kleibergen-Paap rank LM statistic	3370.716	398.908	3365.148	421.611
Kleibergen-Paap rank Wald F statistic	3441.675	399.949	3435.848	422.773

Standard errors in parentheses.
Fixed effects included.
*, *** significance at 10%, and 1%, respectively.
[a] Eco denotes green patents granted to each firm.

4. Empirical results

4.1. Baseline regression results

The panel two-stage least square regression results are shown in Table 3. Column 1 includes only the *industrial sulfur dioxide removal rate (SO_2)* proxy for environmental regulation, along with the control variables. The results show that the coefficient of SO_2 is positive and marginally statistically significant ($\beta_0 = 0.027, P = 0.069$). A 1% point increase in the SO_2 removal rate leads to, on average, a 0.027% increase in firms' eco-innovation. Column 2 includes only the *city PAC expenditure*. The coefficient of *PAC* is positive and statistically significant ($\beta_0 = 0.255, P = 0.000$). A 1% point increase in the PAC expenditure leads to, on average, a 0.255% increase in firms' eco-innovation. Our findings confirm *H1*, suggesting that stronger city environmental regulations stimulate the production of green patents in China. The result for the first stage IV estimation is displayed in Appendix B. The coefficient of the instrument (*Ventilation coefficient*) is negative and significant at 1% significance level.

The coefficients of *R&D* are positive and statistically significant in most specifications—columns 1, 3, and 4 of Table 3—confirming *H2*. A 1% point increase in the R&D expenditure leads to, on average, a 0.004% increase in firms' green patents, suggesting that stronger internal capabilities enhance firms' eco-innovation (column 1). In columns 3 and 4 of Table 3, we further include the interaction terms between the environmental regulation variables and the R&D investment variable (SO_2*R&D, PAC*R&D*), with coefficients of $\beta_2 = 0.019$ ($P = 0.000$) and $\beta_2 = 0.010$ ($P = 0.003$). These results provide strong support to *H3*, and our theoretical remarks that stronger city environmental regulations are effective in converting firms to eco-innovators at the higher level of R&D investment. This implies that technological capabilities need to be strengthened to enable firms to respond appropriately to environmental regulations.

In Table 4, we use human-capital capabilities, which are captured by employee training expenditure (*TRAIN*). The coefficients on *TRAIN* are positive and statistically significant in columns

Table 4. Environmental regulations, capabilities (training), and eco-innovation: two-stage least square estimation

Dependent variable: Eco[a]	**(1)**	**(2)**	**(3)**	**(4)**
SO_2	0.045^{***}		0.043^{***}	
	(0.013)		(0.013)	
PAC		0.326^{***}		0.474^{***}
		(0.115)		(0.160)
$SO_2{}^*TRAIN$			0.011^{***}	
			(0.001)	
PAC^*TRAIN				0.042^{***}
				(0.012)
TRAIN	0.001	0.018^{**}	0.007^{***}	0.026^{***}
	(0.001)	(0.008)	(0.002)	(0.010)
SIZE	0.008	0.039^{*}	0.007	0.069^{**}
	(0.007)	(0.023)	(0.007)	(0.032)
PROFIT	0.062^{***}	0.035^{***}	0.062^{***}	0.029^{**}
	(0.013)	(0.012)	(0.013)	(0.012)
WAGE	0.325^{***}	0.277	0.324^{***}	0.642
	(0.110)	(0.288)	(0.110)	(0.396)
FOREIGN	0.013^{**}	0.007	0.013^{**}	0.005
	(0.005)	(0.005)	(0.005)	(0.005)
ENERGY_CONS	−0.010	−0.020	−0.010	0.055^{**}
	(0.013)	(0.015)	(0.013)	(0.025)
observations	357,172	405,590	357,172	405,590
Kleibergen-Paap rank LM statistic	7477.266	165.178	7444.622	92.007
Kleibergen-Paap rank Wald F statistic	7717.362	165.279	7682.559	92.037

Standard errors in parentheses.
Fixed effects included.
*, **, *** significance at 10%, 5%, and 1%, respectively.
[a] Eco denotes green patents granted to each firm.

2, 3, and 4 of Table 4. These results confirm *H2*: firms that invest more in employee training gain strategic advantage from innovation and become leaders in green markets (Carraro, 2000; Montero, 2002; Rothfels, 2002; Hart, 2004; Popp, 2005). In columns 1 and 2, the coefficients on environmental regulation variables of SO_2 ($\beta_0 = 0.045$, $P = 0.001$) and *PAC* ($\beta_0 = 0.326$, $P = 0.004$) are positive and statistically significant. A 1% point increase in the SO_2 removal rate leads to, on average, a 0.045% increase in firms' eco-innovation. A 1% point increase in the PAC expenditure leads to, on average, a 0.326% increase in firms' eco-innovation. Columns 3 and 4 depict the interaction terms between environmental regulation variables and the employee training expenditure variable (SO_2*TRAIN, PAC* TRAIN*), with coefficients of $\beta_2 = 0.011$ ($P = 0.000$) and $\beta_2 = 0.042$ ($P = 0.001$). The results further verify that stronger capabilities will moderate the relationship between city environmental regulation and a firm's production of green patents. Overall, the baseline regression results support *H3*, indicating that firms' capabilities moderate the relationship between environmental regulations and eco-innovation, as firms with high capabilities can respond to environmental regulation, and consequently can change their innovation processes towards the generation of new knowledge that boosts green patents.

In Table 5, we introduce the *BG* variable, and interact the *BG* variable with the environmental regulation variables (SO_2 and *PAC*). Columns 1 and 2 depict the interaction terms between environmental regulation variables and the *BG* variable (SO_2*BG, PAC*BG*) with coefficients of 0.072 ($P = 0.018$) and 0.306 ($P = 0.000$). The interaction terms are all positive and significant, confirming *H4*. With regard to the magnitude of the impact of environmental regulation on the eco-innovation of affiliated firms and individual firms, the coefficient on innovation in columns 1 and 2 of Table 5 reveals that environmental regulation (proxied by SO_2) leads to a 0.099% increase in eco-innovation in affiliated firms versus a 0.027% increase in individual firms. Alternatively, environmental regulation (proxied by *PAC*) leads to a 0.556% increase in eco-innovation in affiliated firms versus a 0.25% increase in individual firms. The effect size is clearly larger

Table 5. Environmental regulations, business group, and eco-innovation

Dependent variable: Eco[a]	(1)	(2)	(3)	(4)
	Two stage least square estimation		Negative binomial multilevel estimation	
SO_2	0.027^{*}		0.148^{***}	
	(0.016)		(0.025)	
PAC		0.250^{***}		0.265^{***}
		(0.071)		(0.017)
$SO_2{}^{*}BG$	0.072^{**}		0.084^{**}	
	(0.030)		(0.035)	
$PAC^{*}BG$		0.306^{***}		0.102^{***}
		(0.073)		(0.026)
R&D	0.004^{*}	0.003	0.488^{***}	0.509^{***}
	(0.002)	(0.002)	(0.017)	(0.017)
Controls	Yes	Yes	Yes	Yes
observations	259,935	251,885	390,912	359,463
Kleibergen-Paap rank LM statistic	3389.801	424.845		
Kleibergen-Paap rank Wald F statistic	3461.553	426.025		

Standard errors in parentheses. Fixed effects included.
*, **, *** significance at 10%, 5%, and 1%, respectively.
[a] Eco denotes green patents granted to each firm.

for group-affiliated firms, indicating that a group-affiliated firm is more likely to engage in eco-innovation driven by environmental regulations. BG affiliates also benefit from better capabilities and opportunities to share technologies and know-how across the group (Castellacci, 2015), which further increase their ability to eco-innovate. Furthermore, we use a negative binomial multilevel estimation to evaluate the robustness of our analysis. Columns 3 and 4 of Table 5 show that affiliation to a *BG* will further enhance the positive effects of capabilities and environmental regulations on a firm's propensity to produce green patents (0.084 for SO_2*BG, 0.102 for $PAC*BG$). This confirms that our results are robust.

The control variables behave consistently across most specifications. Firm-level control variables—*PROFIT* in Tables 3 and 4, and *SIZE* (column 2 and 4), *WAGE* (column 1 and 3), *FOREIGN* (column 1 and 3), and *ENERGY_CONS* (column 4) in Table 4—are positive and statistically significant. Thus, our results confirm that firm size, average wage, profitability, foreign ownership, and city energy consumption are positively related to eco-innovations in China.

4.2. Robustness checks

4.2.1 Negative binomial multilevel regression results

We proceed with a sensitivity analysis and conduct a set of robustness tests in this section. In Tables 6 and 7, we use a negative binomial multilevel estimation to model over-dispersed count data. The results are consistent with Tables 3 and 4. They show that environmental regulation variables ($SO_{2,}$ *PAC*) have a positive impact on eco-innovation in the context of China. The capabilities variables (*R&D, TRAIN*) positively moderate the effect of environmental regulations on eco-innovation (0.007 for $SO_2*R\&D$, 0.032 for $PAC*R\&D$, 0.029 for $SO_2*TRAIN$, 0.020 for $PAC*TRAIN$). Overall, our results are robust.

4.2.2. Alternative dependent variable

In Table 8, we use the green patents, expressed as a percentage of total patents granted to firms, as the alternative outcome variable. The capabilities variables (*R&D, TRAIN*) positively moderate the effect of environmental regulations on eco-innovation (0.0004 for $SO_2*R\&D$, 0.001 for $PAC*R\&D$, 0.0005 for $SO_2*TRAIN$, 0.006 for $PAC*TRAIN$). Affiliation to a *BG* further enhances the positive effects of environmental regulation on a firm's propensity to produce green patents (0.002 for SO_2*BG, 0.033 for $PAC*BG$). In sum, the results shown in Table 8 are in line with the earlier estimations.

Table 6. Environmental regulations, capabilities (R&D), and eco-innovation: negative binomial multilevel estimation

Dependent variable: Eco[a]	**(1)**	**(2)**	**(3)**	**(4)**
SO_2	0.132*** (0.025)		0.130*** (0.026)	
PAC		0.243*** (0.017)		0.248*** (0.017)
$\boldsymbol{SO_2{}^{*}R\&D}$			0.007 (0.019)	
PAC*R&D				0.032** (0.012)
R&D	0.482*** (0.017)	0.504*** (0.017)	0.484*** (0.018)	0.514*** (0.018)
controls	Yes	Yes	Yes	Yes
observations	390,742	359,297	390,742	359,297

Standard errors in parentheses. Fixed effects included.
*, *** significance at 5%, and 1%, respectively.
[a]Eco denotes green patents granted to each firm (count variable).

Table 7. Environmental regulations, capabilities (training), and eco-innovation: negative binomial multilevel estimation

Dependent variable: Eco[a]	**(1)**	**(2)**	**(3)**	**(4)**
SO_2	0.214*** (0.024)		0.191*** (0.024)	
PAC		0.270*** (0.018)		0.270*** (0.018)
$\boldsymbol{SO_2{}^{*}TRAIN}$			0.092*** (0.021)	
PAC*TRAIN				0.020* (0.011)
TRAIN	0.080*** (0.020)	0.111*** (0.020)	0.129*** (0.023)	0.114*** (0.020)
controls	Yes	Yes	Yes	Yes
Observations	520,959	490,654	520,959	490,654

Standard errors in parentheses.
Fixed effects included.
*, *** significance at 10%, and 1%, respectively.
[a]Eco denotes green patents granted to each firm (count variable).

5. Concluding discussion

We set out to investigate the relationship between subnational environmental regulations and eco-innovation by considering the contingency of firms' heterogeneous capabilities and ownership characteristics. Our findings indicate that stronger city environmental regulations have a positive impact on eco-innovation activities. Moreover, we find that the impact of city-level regulations is enhanced by both internal firm capabilities and existing ownership structures, such as affiliation with a BG. These findings attest to some of the boundary conditions for subnational institutional effects on firm behaviors and strategies, complementing previous literature on the role of R&D investments in promoting sustainability through eco-innovations (Canon-De-Francia *et al.*, 2007; Costantini *et al.*, 2015; Demirel and Kesidou, 2019).

We make several contributions to the existing literature. First, we extend and enrich the eco-innovation literature by pointing out the importance of other capabilities, beyond just R&D, that firms should attempt to build and develop. Our research demonstrates that firms which invest in internal capabilities, such as human capital development through training, are more likely to produce green patents. This approach highlights the role of internal organizational efforts, complementing prior work in this area that has focused on the importance of external efforts through an open-innovation approach (Ghisetti *et al.*, 2015; Kennedy *et al.*, 2017).

Table 8. Alternative dependent variable: two-stage least square estimations

Dependent variable: Ecop[a]	(1)	(2)	(3)	(4)	(5)	(6)
SO_2	0.002^{*} (0.001)		0.003^{**} (0.001)		0.002^{*} (0.001)	
PAC		0.028^{***} (0.007)		0.074^{***} (0.016)		0.028^{***} (0.007)
$SO_2{}^{*}R\&D$	0.0004^{*} (0.0002)					
$PAC^{*}R\&D$		0.001^{***} (0.000)				
$SO_2{}^{*}TRAIN$			0.0005^{***} (0.0001)			
$PAC^{*}TRAIN$				0.006^{***} (0.001)		
$SO_2{}^{*}BG$					0.002 (0.003)	
$PAC^{*}BG$						0.033^{***} (0.007)
R&D	0.001^{***} (0.000)	0.001^{***} (0.000)			0.001^{***} (0.000)	0.001^{***} (0.000)
TRAIN			0.0004^{***} (0.0002)	0.005^{***} (0.001)		
controls	Yes	Yes	Yes	Yes	Yes	Yes
observations	259,935	251,885	357,172	405,590	259,935	251,885
Kleibergen-Paap rank LM statistic	3365.148	421.611	7444.622	92.007	3389.801	424.845
Kleibergen-Paap rank Wald F statistic	3435.848	422.773	7682.559	92.037	3461.553	426.025

Standard errors in parentheses.
Fixed effects included.
*, **, *** significance at 10%, 5%, and 1%, respectively.
[a] Ecop denotes green patents over total patents granted to each firm.

Second, we document moderators for the effects of subnational institutions on eco-innovation. Specifically, we emphasize the role of internal capabilities in moderating the relationship between environmental regulation and eco-innovation. This relationship is stronger for firms that invest in R&D and/or training. This contribution advances the eco-innovation literature by suggesting that capabilities give firms the freedom (Sen, 2009)—associated with the identification of a range of opportunities and options (Scerri, 2012)—to respond appropriately to environmental regulations.

Finally, we contribute to the broader management literature by examining the role of ownership choices as a potentially omitted insight into what drives eco-innovation. We do so by showing that for firms affiliated with a BG, the relationship between environmental regulation and eco-innovation is stronger. This is crucial for a comprehensive understanding of the direct and indirect role that firm heterogeneity plays in boosting the generation of green patents, and ultimately in enabling green and sustainable city development.

In addition to academic contributions, we draw on valuable policy insights, particularly salient for emerging economies striving to incentivize firms to become greener. First, given the pressing threats of global warming, city and regional policymakers in emerging economies should set stringent environmental regulations to encourage firms in their areas to develop more green technologies. Second, policymakers can enhance firms' capabilities by funding R&D and labor training. These technological capabilities enable firms to develop more green patents, which have the potential to address long-term environmental challenges facing humanity. Finally, combining environmental regulations with technology policies can further enhance firms' capabilities. This policy mix effectively supports the development of low-carbon, high-efficiency technologies (Rogge and Reichardt, 2016; Uyarra *et al.*, 2016; Rogge and Schleich, 2018; Edmondson *et al.*, 2019; Kern *et al.*, 2019) as well as skill-upgrading policies at the organizational level (Marin and Vona, 2019). Our results strongly support such complementarity, offering novel and relevant insights for policymakers worldwide seeking to meet the stringent pollution targets, set through global agreements such as the United Nations Framework Convention on Climate Change Conference of the Parties (COP) annual meetings.

Tackling pollution and climate change challenges demands the mobilization of many resources across individuals, organizations, and governments (Krammer, 2024). Our study suggests that subnational institutional requirements implemented at the level of city jurisdictions serve as effective tools for encouraging organizations to produce green technologies. Furthermore, we identify important synergies with existing firm-level capabilities and certain organizational structures (i.e., BGs) that rely on reputation and have a broader reach, making them more responsive to these incentives.

Although the use of green patents to measure eco-innovation has the advantage of being a continuous and relatively objective measure, it is important to note that not all eco-innovation outcomes are being patented, and patented eco-innovations could be of different quality. However, information for alternative eco-innovation measures, such as patent citations, is unavailable in our dataset. Future research, therefore, should test the validity of these findings using alternative measures of eco-innovation.

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Appendix A

Table A. Percentage of firms in each city (column A) and percentage of energy consumption in each city (column B)[a]

Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)
Ankang	0.05	0.21	Anqing	0.27	0.23	Anshan	0.37	0.45
Anshun	0.04	0.19	Anyang	0.20	0.47	Baicheng	0.04	0.19
Baishan	0.08	0.18	Baiyin	0.03	0.14	Baoding	0.66	0.57
Baoji	0.10	0.20	Baoshan	0.02	0.21	Baotou	0.13	0.36
Bayan Nur	0.06	0.36	Bazhong	0.03	0.40	Beihai	0.04	0.17
Beijing	2.05	0.15	Bengbu	0.12	0.23	Benxi	0.11	0.46
Binzhou	0.24	0.74	Bose	0.05	0.17	Bozhou	0.09	0.24
Cangzhou	0.47	0.59	Changchun	0.24	0.18	Changde	0.21	0.30
Changsha	0.40	0.31	Changzhi	0.13	0.37	Changzhou	1.59	0.53
Chaohu	0.16	0.21	Chaoyang	0.19	0.45	Chaozhou	0.20	0.58
Chengde	0.22	0.56	Chengdu	0.74	0.39	Chenzhou	0.25	0.29
Chifeng	0.11	0.35	Chizhou	0.06	0.23	Chongqing	1.05	0.16
Chongzuo	0.03	0.18	Chuzhou	0.22	0.23	Dalian	0.89	0.45
Dandong	0.30	0.43	Daqing	0.14	0.24	Datong	0.13	0.35
Dazhou	0.08	0.40	Deyang	0.23	0.39	Dezhou	0.71	0.74
Dingxi	0.02	0.14	Dongguan	0.54	0.64	Dongying	0.20	0.74
Erdos	0.10	0.33	Ezhou	0.11	0.33	Fangchenggang	0.02	0.19
Foshan	1.34	0.58	Fushun	0.20	0.47	Fuxin	0.14	0.45
Fuyang	0.13	0.24	Fuzhou	0.83	0.20	Fuzhou	0.17	0.14
Ganzhou	0.21	0.14	Guang'an	0.07	0.40	Guangyuan	0.05	0.41
Guangzhou	1.80	0.54	Guigang	0.05	0.19	Guilin	0.16	0.17
Guiyang	0.15	0.18	Guyuan	0.01	0.09	Haikou	0.03	0.03
Handan	0.26	0.60	Hangzhou	2.73	0.35	Hanzhong	0.05	0.20
Harbin	0.29	0.25	Hebi	0.11	0.46	Hechi	0.05	0.17
Hefei	0.40	0.23	Hegang	0.03	0.25	Heihe	0.02	0.25
Hengshui	0.35	0.58	Hengyang	0.21	0.30	Heyuan	0.06	0.61
Heze	0.34	0.78	Hezhou	0.03	0.18	Hohhot	0.09	0.35

(continued)

Table A. (Continued)

Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)
Huaian	0.45	0.56	Huaibe	0.08	0.24	Huaihua	0.10	0.30
Huainan	0.07	0.24	Huanggang	0.23	0.34	Huangshan	0.10	0.23
Huangshi	0.11	0.34	Huizhou	0.37	0.58	Huludao	0.09	0.45
Hulunbeier	0.07	0.37	Huzhou	0.76	0.36	Jiamusi	0.17	0.23
Ji’an	0.19	0.14	Jiangmen	0.69	0.55	Jiaozuo	0.43	0.45
Jiaxing	1.62	0.36	Jiayuguan	0.01	0.14	Jieyang	0.29	0.61
Jilin	0.34	0.18	Jinan	0.47	0.72	Jinchang	0.01	0.13
Jincheng	0.11	0.37	Jingdezhen	0.07	0.14	Jingmen	0.14	0.34
Jingzhou	0.44	0.30	Jinhua	1.13	0.36	Jining	0.47	0.72
Jinzhong	0.17	0.38	Jinzhou	0.23	0.44	Jiujiang	0.18	0.14
Jiuquan	0.04	0.14	Jixi	0.04	0.24	Kaifeng	0.21	0.47
Karamay	0.03	0.20	Kunming	0.23	0.20	Laibin	0.03	0.18
Laiwu	0.07	0.76	Langfang	0.31	0.59	Lanzhou	0.13	0.13
Leshan	0.15	0.38	Lianyungang	0.45	0.56	Liaocheng	0.34	0.78
Liaoyang	0.22	0.44	Liaoyuan	0.06	0.18	Lijiang	0.02	0.19
Lincang	0.02	0.20	Linfen	0.29	0.35	Linyi	0.68	0.75
Lishui	0.30	0.37	Liupanshui	0.03	0.20	Liuzhou	0.18	0.18
Longnan	0.02	0.13	Longyan	0.22	0.21	Loudi	0.10	0.31
Lu’an	0.18	0.23	luohe	0.19	0.45	Luoyang	0.37	0.46
Luzhou	0.10	0.39	Lvliang	0.47	0.34	Maanshan	0.09	0.24
Maoming	0.21	0.56	Meishan	0.10	0.40	Meizhou	0.09	0.57
Mianyang	0.23	0.37	Mudanjiang	0.12	0.25	Nanchang	0.33	0.14
Nanchong	0.12	0.39	Nanjing	1.13	0.54	Nanning	0.22	0.17
Nanping	0.22	0.21	Nantong	1.50	0.55	Nanyang	0.42	0.45
Neijiang	0.10	0.39	Ningbo	3.28	0.35	Panjin	0.11	0.47
Panzhihua	1.94	0.29	Pingdingshan	0.16	0.46	Pingliang	0.03	0.14
Pingxiang	0.15	0.14	Pu’er	0.02	0.21	Putian	0.24	0.21
Puyang	0.18	0.46	Qingdao	1.53	0.72	Qingyang	0.06	0.13
Qingyuan	0.10	0.60	Qinhuangdao	0.15	0.58	Qinzhou	0.05	0.18

(continued)

Table A. (Continued)

Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)
Qiqihar	0.28	0.24	Qitaihe	0.02	0.25	Quanzhou	1.53	0.20
Qujing	0.08	0.20	Quzhou	0.29	0.36	Rizhao	0.16	0.73
Sanmenxia	0.17	0.46	Sanming	0.38	0.21	Sanya	0.01	0.03
Shanghai	5.52	0.23	Shangluo	0.02	0.22	Shangqiu	0.14	0.48
Shangrao	0.15	0.14	Shantou	0.49	0.56	Shanwei	0.20	0.51
Shaoguan	0.10	0.59	Shaoxing	1.36	0.36	shaoyang	0.16	0.30
Shenyang	1.52	0.42	Shenzhen	1.39	0.57	Shijiazhuang	0.92	0.58
Shiyan	0.11	0.34	Shizuishan	0.04	0.09	Shuangyashan	0.06	0.23
Shuozhou	0.09	0.37	Siping	0.07	0.18	Songyuan	0.07	0.19
Suihua	0.08	0.24	Suining	0.06	0.40	Suizhou	0.15	0.33
Suqian	0.38	0.59	Suzhou	2.93	0.55	Suzhou	0.11	0.24
Tai’an	0.37	0.74	Taiyuan	0.19	0.37	Taizhou	0.84	0.55
Taizhou	1.70	0.35	Tangshan	0.56	0.57	Tianjin	1.93	0.15
Tianshui	0.03	0.14	Tieling	0.25	0.46	Tongchuan	0.02	0.20
Tonghua	0.12	0.17	Tongliao	0.10	0.38	Tongling	0.06	0.22
Ulanqab	0.08	0.34	Urumqi	0.13	0.21	Weifang	1.12	0.72
Weihai	0.69	0.72	Weinan	0.07	0.20	Wenzhou	2.23	0.35
Wuhai	0.10	0.29	Wuhan	0.53	0.33	Wuhu	0.26	0.23
Wuwei	0.03	0.13	Wuxi	2.09	0.53	Wuzhong	0.03	0.09
Wuzhou	0.07	0.18	Xi’an	0.27	0.19	Xiamen	0.56	0.20
Xiangfan	0.19	0.36	Xiangtan	0.15	0.30	Xianning	0.13	0.34
Xianyang	0.12	0.21	Xiaogan	0.28	0.33	Xingtai	0.41	0.57
Xinxiang	0.41	0.43	Xinyang	0.20	0.47	Xinyu	0.07	0.14
Xinzhou	0.09	0.38	Xuancheng	0.18	0.23	Xuchang	0.33	0.46
Xuzhou	0.69	0.56	Ya’an	0.07	0.38	Yan’an	0.03	0.19
Yancheng	0.94	0.54	Yangjiang	0.11	0.58	Yangquan	0.07	0.37
Yangzhou	0.89	0.55	Yantai	1.06	0.71	Yibin	0.12	0.39
Yichang	0.19	0.35	Yichun	0.07	0.22	Yichun	0.17	0.14
Yinchuan	0.09	0.09	Yingkou	0.36	0.45	Yingtan	0.04	0.15

(continued)

Table A. (Continued)

Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)	Cities	Firms (%)	Energy consumption (%)
Yiyang	0.16	0.30	Yongzhou	0.13	0.30	Yueyang	0.23	0.31
Yulin	0.12	0.18	Yulin	0.09	0.20	Yuncheng	0.16	0.38
Yunfu	0.09	0.62	Yuxi	0.08	0.19	Zaozhuang	0.40	0.73
Zhangjiajie	0.02	0.31	Zhangjiakou	0.12	0.62	Zhangye	0.03	0.14
Zhangzhou	0.43	0.21	Zhanjiang	0.18	0.57	Zhaoqing	0.33	0.58
Zhaotong	0.03	0.21	Zhengzhou	0.88	0.45	Zhenjiang	0.79	0.55
Zhongshan	0.44	0.63	Zhongwei	0.02	0.09	Zhoukou	0.22	0.47
Zhoushan	0.16	0.36	Zhuhai	0.36	0.56	Zhumadian	0.26	0.47
Zhuzhou	0.24	0.30	Zibo	0.80	0.74	Zigong	0.11	0.40
Ziyang	0.10	0.41	Zunyi	0.09	0.19			

[a] Column A is calculated by the total number of firms in a city divided by the total number of firms in all cities. Column B is calculated by the energy consumption of a city divided by the total energy consumption of all cities.

Appendix B

The first stage of IV estimation

Table B. Environmental regulations, capabilities (R&D), and eco-innovation: two-stage least square estimations

Dependent variable	First stage SO_2	Second stage *Eco*$^{\alpha}$	First stage *PAC*	Second stage *Eco*^{a}
Ventilation coefficient	–0.920***		–0.304***	
	(0.016)		(0.015)	
SO_2		0.027*		
		(0.014)		
PAC				0.255***
				(0.072)
R&D	0.027***	0.004*	0.002	0.003
	(0.002)	(0.002)	(0.002)	(0.002)
SIZE	0.441***	0.012	0.128***	0.011
	(0.005)	(0.010)	(0.004)	(0.012)
PROFIT	0.018	0.088***	0.005	0.078***
	(0.015)	(0.016)	(0.012)	(0.018)
WAGE	0.273***	0.169	0.141***	0.156
	(0.011)	(0.127)	(0.009)	(0.165)
FOREIGN	0.010	0.010	0.009*	0.004
	(0.006)	(0.007)	(0.005)	(0.007)
ENERGY_CONS	0.944***	0.009	0.082***	0.005
	(0.010)	(0.020)	(0.008)	(0.015)
observations	259,935	259,935	251,885	251,885
Kleibergen-Paap rank LM statistic		3370.716		398.908
Kleibergen-Paap rank Wald F statistic		3441.675		399.949

Standard errors in parentheses.
Fixed effects included.
*, *** significance at 10%, and 1%, respectively.
[a] Eco denotes green patents granted to each firm.

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