A study on the differential effects of heterogeneous environmental regulations on the green transformation of Chinese manufacturing enterprises under "Double Carbon" target

Yongjun Tang [a], Yuqiu Qi [a], Fen Zhou [b,*], Lei Hua [c]

[a] School of Business, Hohai University, Focheng West Road 8, Nanjing, 211100, China
[b] School of Accounting, Nanjing University of Finance & Economics, Wenyuan Road 3, Nanjing, 210023, China
[c] School of Management, Tianjin University of Technology, Binshui West Road 391, Tianjin, 300382, China

ARTICLE INFO

ABSTRACT

Using panel data of Chinese manufacturing enterprises listed in Shanghai and Shenzhen A-shares from 2015 to 2021, we examine the effects of heterogeneous environmental regulations on the green transformation of Chinese manufacturing enterprises under "Double Carbon" target, and reveal the mediating role played by managers' green perception in the process from an intra-firm perspective. We find that three environmental regulation tools, namely environmental administrative supervision, environmental economic regulation and environmental soft constraint, all contribute significantly to the green transformation of manufacturing enterprises. Among them, environmental economic regulation is the most effective in promoting the green transformation of manufacturing enterprises, followed by environmental soft constraint and environmental administrative supervision. The mechanism analysis shows that managers' green perception is partially mediated between heterogeneous environmental regulations and the green transformation of manufacturing enterprises. Moreover, environmental administrative supervision is the most effective in raising managers' green perception among them, followed by environmental economic regulation and environmental soft constraint. Further analysis shows that the positive effect of heterogeneous environmental regulations on the green transformation of Chinese manufacturing enterprises is more significant when the enterprises locate in regions with high policy uncertainty, in the eastern part of the country, or when the enterprises are state-owned enterprises. The conclusions provide a theoretical basis for Chinese environmental policy-makers to flexibly adopt differentiated environmental regulation tools.

1. Introduction

Since Reform and Opening-up from 1978, China's economy has continued to grow at a rapid pace. Until 2022, Chinese manufacturing sector accounts for nearly 30% of global value added and has become the world's largest manufacturing sector for 13 consecutive years [1,2]. However, the high level of carbon emissions caused by the traditional development model of manufacturing with high input, energy consumption, and pollution have put enormous pressure on China's environmental management and sustainable development [3,4]. In response, in September 2020, Chinese President Xi Jinping proposed at the United Nations General

Assembly the goal of achieving carbon peaking by 2030 and carbon neutrality by 2060 [5,6]. To achieve " Double Carbon " target, the Chinese government has developed a series of policies to promote the green transformation and upgrading of traditional manufacturing industries [7].

Nevertheless, in the reality of increasingly fierce market competition and tightening resource constraints, Chinese manufacturing enterprises are generally caught in the dilemma of insufficient endogenous motivation for green transformation, which restricts the enhancement of the green transformation effect [8]. Given the multiple challenges, how to break through the bottleneck of green transformation in the manufacturing industry and promote "Double Carbon" target and China's high-quality economic development strategy in an orderly manner is a significant issue that needs to be addressed by the theoretical and academic communities [9]. Extensive researches have focused on the analysis of the drivers and mechanisms of green transformation of manufacturing industries at macro and mesoscopic levels [10–13], while researches on micro-enterprises have focused more on the external drivers of the level of green technology innovation, neglecting the direct research on the effect of green transformation on manufacturing enterprises and their internal drivers [14–16]. In addition, most scholars have conducted empirical studies on the measurement indicators of green transformation in manufacturing based on a single indicator, such as green total factor productivity [17,18], which lacks comprehensiveness, universality, and objectivity.

By mobilizing resources from the government, the market, and the public, environmental regulations intervene and correct the "market failure" in ecological protection, to provide a new opportunity for the green transformation of the manufacturing industry, which has become an essential tool to accelerate the green transformation of the manufacturing industry in recent years [19]. Currently, there is a lot of discussion in academia about whether environmental regulations can facilitate the green transformation of manufacturing enterprises, with three basic views: "innovation compensation", "compliance cost" and complex uncertainty [20–22]. Further, scholars have found that environmental regulations can be broadly classified into three instruments: command-and-control environmental regulation, market-incentive environmental regulation, and public-voluntary environmental regulation [23,24]. Depending on their regulatory objectives, enforcement strength, enforcement methods, and enforcement costs, the effects of these three types of environmental regulations on green innovation in manufacturing enterprises also vary [25]. However, most of the existing studies have investigated the effects of a single environmental regulation tool from the perspective of green innovation [26–28], and there need to be more comprehensive and objective comparative empirical studies on the differentiated effects of heterogeneous environmental regulation tools from the perspective of green transformation in manufacturing. In addition, most of the existing studies have discussed the effects of environmental regulations from a top-down perspective [29–33], and there need to be more bottom-up studies on the response measures taken by enterprises to environmental regulations.

Based on the above research status, this study poses the following research questions. First, are there differences in the effects of heterogeneous environmental regulation tools on the green transformation of Chinese manufacturing enterprises? Second, what are the internal response mechanisms of Chinese manufacturing enterprises when faced with heterogeneous environmental regulation tools? Third, how can heterogeneous environmental tools be applied differently to maximize their effectiveness in China's complex and unique administrative system? The discussion of the above questions is vital for promoting the green transformation of Chinese manufacturing enterprises and achieving "Double Carbon" target on schedule. Therefore, this study uses the panel data of China manufacturing enterprises listed in Shanghai and Shenzhen A-shares from 2015 to 2021, which can fully represent the level of green transformation of Chinese manufacturing enterprises, and makes an empirical study on the differential effect between heterogeneous environmental regulations and green transformation of manufacturing enterprises under "Double Carbon" target by using the fixed effect model. Further, this study profoundly analyzes the response mechanism of manufacturing enterprises to heterogeneous environmental regulation from the perspective of managers' green perception, which aims to provide theoretical basis and experience for relevant government departments in China to promote "Double Carbon " target better.

Compared with existing literature, this study has three marginal contributions. In terms of theory, we put heterogeneous environmental regulations, the green transformation of manufacturing enterprises, and managers' green perception into the same research framework, which not only verifies the differentiated effect of heterogeneous environmental regulations on the green transformation of manufacturing enterprises in China, but also further examines the response mechanism of enterprises to heterogeneous environmental regulations from the perspective of managers' green perception. Through empirical analysis, this study finds that environmental economic regulation has the best promotion effect on the green transformation of manufacturing enterprises, followed by environmental soft constraint and environmental administrative supervision. Managers' green perception plays a partial mediating role between heterogeneous environmental regulations and the green transformation of manufacturing enterprises. The conclusions enrich and expand the research scope of environmental regulation theory and strategic cognition theory, and provide a reference for developing countries under the background of the green transformation. In terms of method, we build an evaluation system for the green transformation degree of manufacturing enterprises from four dimensions: green system, green operation, green governance, and green responsibility, and make a comprehensive and objective evaluation of the level of green transformation of manufacturing enterprises, which makes up for the lack of reliability and scientificity due to the single index in the existing literature. In addition, we use the year-industry double fixed effect model as the empirical method, excluding the influence of other confounding factors. The conclusions can not only accurately provide micro-evidence of the impact of heterogeneous environmental regulations on the green transformation of manufacturing enterprises in China, but also reveal the long-term dynamic effect of the green transformation of manufacturing enterprises in China under "Double Carbon" target. In terms of practice, based on the unique institutional background and current situation of environmental regulations in China, we discussed the differentiated use scenarios of heterogeneous environmental regulations and the positive mediating role played by managers' green perception between heterogeneous environmental regulations and green transformation of manufacturing enterprises. The conclusions can provide theoretical guidance for Chinese environmental policymakers to adopt differentiated environmental policy tools according to specific conditions, and to promote the

green transformation of manufacturing enterprises by cultivating managers' green perception. It is helpful to make up for the lack of operability and internal perspective in the existing literature on environmental policy implementations.

The rest of the study is structured as follows. Section 2 compares the relevant research results on environmental regulations and the green transformation of the manufacturing industry. Section 3 describes the process of the role of heterogeneous environmental regulation tools and green transformation of manufacturing enterprises, and then puts forward the research hypotheses. Section 4 introduces the empirical data sources, variable definitions, and empirical models. Section 5 analyses the basic regression results. Section 6 further discusses the empirical results from the perspective of the mechanism of action and heterogeneity. Section 7 presents the conclusions; policy implements and limitations.

2. Literature review

The literature related to the research theme of this study can divide into two main branches: the first is related to environmental regulations, including the classification of environmental regulation tools and their micro effects; the second is related to the green transformation of manufacturing, including the measurement of the green transformation of manufacturing and its driving factors.

2.1. Relevant literature on environmental regulations

Environmental regulation is a form of binding government intervention and restriction on the use of environmental resources by market players through the "visible hand" to address market failures caused by the negative externalities of environmental pollution [34–36]. In practice, environmental regulations can be divided into three categories: command-and-control environmental regulation, market-incentive environmental regulation, and public-voluntary environmental regulation, depending on the objectives, subjects, methods, and intensity of implementation [37–39].

Regarding the economic and environmental consequences of environmental regulations on manufacturing enterprises, scholars have conducted many studies on the existence of the Porter Hypothesis [20,40]. However, the main views are not unified and fall into the following three categories. The first is the facilitative role. Some scholars argue that environmental regulations can 'push' high-polluting enterprises to focus on green innovation and increase their willingness to innovate green technology, Therefore, environmental regulations can significantly reduce manufacturing enterprises' emission levels and operating costs, and positively contributes to their competitiveness, financial performance, and green total factor productivity [41–43]. The second is the disincentive role. Some scholars argue that environmental regulations have a "crowding out" effect on manufacturing firms, i.e., they increase the cost of production and operation, which not only fails to motivate enterprises to innovate green but also weakens their production capacity [44–47]. Thirdly, the effect of uncertainty. Some scholars argue that the impact of environmental regulations on manufacturing enterprises is not simply linear and that, as environmental regulations strengthen, the level of technological innovation, economic efficiency, and environmental performance of firms will show a positive 'U' shape, an inverted 'U' shape or an uncertain relationship [48–51]. Further, Chinese scholars have explored the effects of environmental regulations on green innovation from the perspective of heterogeneous environmental regulation tools, suggesting that the effects of the three instruments on the level of green innovation of enterprises vary positively or negatively depending on the implementation cycle, the intensity of implementation and the internal management of enterprises. However, a unified conclusion has yet to be reached [52–55].

In summary, the existing literature on environmental regulations lacks a comprehensive empirical analysis of the micro effects of environmental regulations from the perspective of manufacturing enterprises' green transformation level, and also lacks a comparison of the effects of different environmental regulation tools on each other, thus neglecting the study of the differences in the use scenarios of heterogeneous environmental regulation tools.

2.2. Relevant literature on the green transformation of the manufacturing industry

Green transformation of the manufacturing industry refers to a modern manufacturing mode with energy saving as the guide and technological innovation as the core, by way of the intensive utilization of energy and the reduction of unexpected output pollutants in the production process, to realize the win-win economic and ecological benefit [56,57]. As the global climate deterioration problem becomes more and more serious, the green transformation of the manufacturing industry has gradually attracted extensive attention from academics, mainly focusing on the measurement and driving factors of the green transformation of the manufacturing industry [58,59].

Regarding the measurement of green transformation of the manufacturing industry, scholars have not yet reached a consensus, and most of them use single indicators based on production efficiencies, such as value-added rate and green total factor productivity, to measure [60,61]. Further, some scholars question the comprehensiveness of single indicators, and use hierarchical analysis, principal component analysis, and entropy power method to construct a comprehensive evaluation index system from dimensions such as intensive use of energy resources, pollution emission reduction, green technological innovation, industrial structure upgrading and sustainable development, but the evaluation angles are not uniform [62,63]. In terms of the driving factors of green transformation of the manufacturing industry, scholars mainly discuss the influencing factors of manufacturing transformation from macro perspectives, such as environmental regulations, financial support, digital empowerment, industrial agglomeration, and global value chain [64–69], and micro perspectives such as capital investment, technological innovation, and digital transformation [70–74]. Among the studies on environmental regulations and green transformation of the manufacturing industry, it is believed that environmental regulations can trigger an "innovation compensation" effect in the long run, pushing out energy-intensive and polluting industries from the

market, thus promoting the upgrading of the manufacturing industry structure to achieve green total factor productivity [75,76].

In summary, the existing literature on the green transformation of the manufacturing industry lacks a comprehensive indicator system to compare the differential impact of heterogeneous environmental regulation tools on manufacturing enterprises' overall level of green transformation. Also, the existing literature ignores the bottom-up response of micro-enterprises to environmental regulations from the perspective of enterprise interior, which plays an important role in the process of green transformation of enterprises.

3. Theoretical analysis and hypotheses development

According to the literature mentioned above on environmental regulation and the green transformation of the manufacturing industry, combined with the realistic background that the green transformation of the manufacturing industry is urgently needed under "Double Carbon" target in China, we believe that there is an inseparable relationship among heterogeneous environmental regulations and the green transformation of manufacturing enterprises. Moreover, managers' green perception is essential to manufacturing enterprises' response to environmental regulation and green transformation strategy. Therefore, this study further analyzes the relationship among heterogeneous environmental regulation, the green transformation of manufacturing enterprises, and managers' green perception, and then puts forward the research hypothesis of this study.

3.1. Heterogeneous environmental regulations and green transformation of manufacturing enterprises

3.1.1. Environmental administrative supervision and green transformation of manufacturing enterprises

Environmental administrative supervision influences manufacturing enterprises to make decisions conducive to environment through legislation or the promulgation of policy systems in three aspects: ex-ante, ex-post, and ex-post. In the ex-ante control stage, the government urges enterprises to incorporate environmental efficiency as a core element in the formulation and implementation of their development strategies to enhance their green transformation performance by formulating a series of environmental planning, environmental performance evaluation, and other eco-environmental protection systems [77,78]. In the ex-post control stage, the government restricts resource use and pollutant emissions by setting emission permits and bans, controlling the total amount of pollutant emissions, Etc. In order to meet the legal requirements, enterprises can only choose to optimize and upgrade their production technologies to enhance their green transformation [61,79]. In the ex-post stage, the government exercises its power to punish enterprises whose emissions exceed the standards by enforcing environmental protection regulations. In order to avoid economic losses and negative images caused by environmental penalties, enterprises will actively respond to relevant government policies, stimulating their subjective initiative to implement green transformation strategies [80,81]. Therefore, the following hypothesis is proposed.

H1a. Environmental administrative regulation promotes the green transformation of manufacturing enterprises.

3.1.2. Environmental economic regulation and green transformation of manufacturing enterprises

Environmental economic regulation changes the costs or benefits of the emitters through the market price mechanism, prompting manufacturing enterprises to internalize the environmental costs, thus stimulating them to carry out green technological innovation and enhancing the green transformation from both the internal enterprises and the market environment [82,83]. From the perspective of internal enterprises, environmental economic regulation can effectively alleviate the financing constraint and uncertainty risks faced by enterprises in the process of implementing green technology innovation [84]. It can also use market transactions to closely link environmental benefits with economic benefits, stimulating enterprises to shift from passively meeting legal requirements to actively promoting green transformation and increasing their motivation for green transformation [85,86]. From the perspective of the market environment, environmental economic regulation releases positive signals on environmental governance to all sectors of society by increasing the level of government investment in environmental infrastructure and pollution control [87]. It's useful to guide relevant investors to pay more attention to the green development of enterprises, thus creating a favorable social environment for the green transformation of enterprises [88,89]. Therefore, the following hypothesis is proposed.

H1b. Environmental economic regulation promotes the green transformation of manufacturing enterprises.

3.1.3. Environmental soft constraint and green transformation of manufacturing enterprises

Environmental soft constraint is self-regulatory mechanisms based on voluntary, consensual, and individual adoption of specific standards [90]. The most crucial feature of soft environmental constraint is that they are non-compulsory, i.e., enterprises follow voluntary principles and give full play to their initiative in order to meet the requirements and expectations of society and the public for their green development [91]. In participating in environmental soft constraint, enterprises can fully demonstrate their environmental awareness and responsibility to build up a green image, thus helping them improve their green transformation [92,93]. On the one hand, given the increasing level of environmental regulations and information asymmetry, enterprises will choose to actively implement green transformation behavior in response to pressure from stakeholders, government and the public [94]. On the other hand, when enterprises take the initiative to implement cleaner production, they will release positive signals to the community that they meet the requirements of green, low-carbon, and circular development, thus enhancing their legitimacy [95]. Therefore, the following hypothesis is proposed.

Hypothesis 1c. Environmental soft constraint promotes the green transformation of manufacturing enterprises.

3.2. Heterogeneous environmental regulation and the mechanism of green transformation of manufacturing enterprises

3.2.1. Heterogeneous environmental regulations and managers' green perception

A large body of research based on individual perceptions has generally concluded that external pressures can have a significant impact on individual awareness and behavior [96]. It follows that external regulatory pressures can also have an impact on the level of managers' green perception [37]. Managers' green perception can be divided into green risk and benefit perception. Green risk perception refers to managers' sensitivity and ability to perceive the risk of ecological problems to the long-term development of the company, and the risk of damage to the ecological environment caused by the company's actions based on the motive of legitimacy and social responsibility; green benefit perception refers to managers' sensitivity and ability to perceive the risk of development and the risk of damage to the ecological environment caused by the company's actions based on the motive of profit-seeking [97]. From the perspective of green risk perception, environmental regulations can increase the business risk, competition risk, and ecological damage risk faced by enterprises, which can enhance managers' perception of green risk; from the perspective of green benefit perception, environmental regulations can alleviate enterprises' financing constraint and increase their potential green revenue, which can enhance managers' perception of green benefit [96,98]. Therefore, the following hypotheses are proposed.

H2a. Environmental administrative supervision promotes managers' green perception.

H2b. Environmental economic regulation promotes managers' green perception.

H2c. Environmental soft constraint promotes managers' green perception.

3.2.2. Managers' green perception and green transformation of manufacturing enterprises

Both higher-order theory and strategic cognitive theory emphasize that managers make strategic decisions about their environment based on their subjective perceptions of values and mindsets [99,100]. Therefore, managers' concern and awareness of environmental protection issues are critical to implementing green development strategies and improving green development [101,102]. Specifically, managers with a strong perception of green risks pay more attention to the green performance of the company's production technology for social responsibility reasons [103]. They will upgrade or replace production technologies that were previously high in energy consumption and pollution by introducing pollutant treatment equipment and purchasing green resources, to improve the level of green transformation of the company and reduce the environmental pollution caused by the production process [104]. In order to find out the identification of opportunities, managers with a strong perception of green benefit will create a differentiated green competitive advantage by increasing environmental investment and green input, using green technology innovation to reduce production and operation costs, and actively sending green signals to the outside world through green publicity and environmental training to establish an environmentally friendly corporate image [105,106]. Therefore, the following hypothesis is proposed.

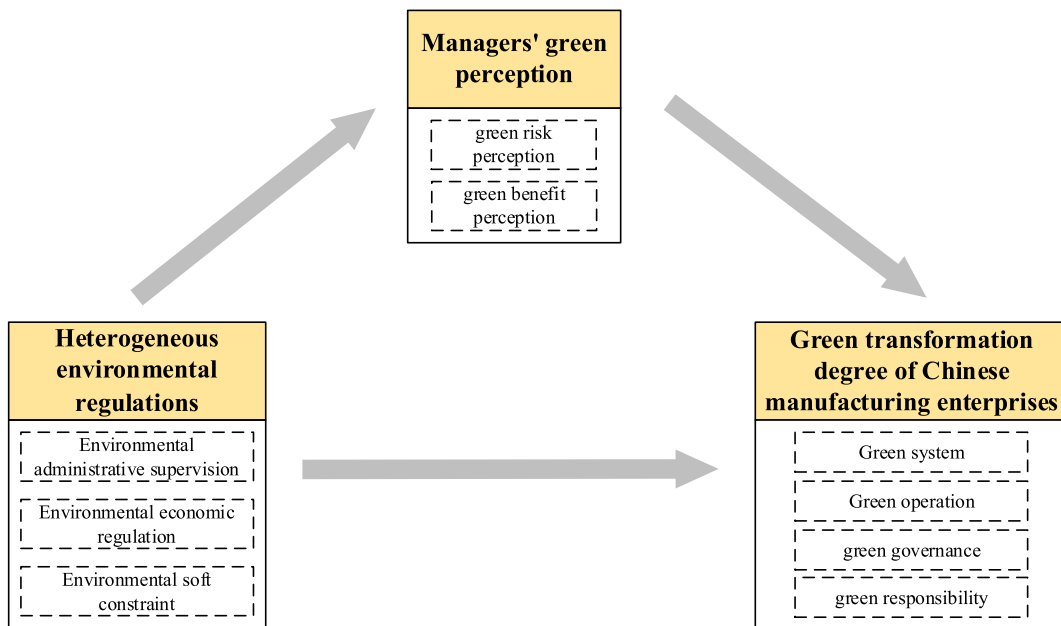**H3.** Managers' green perception promotes the green transformation of manufacturing enterprises.

Fig. 1. Hypothetical train of thought.

3.2.3. Heterogeneous environmental regulation, managers' green perception and green transformation of manufacturing enterprises

As research on the relationship between environmental regulations and enterprise development continues to intensify, scholars have found that, despite the same environmental regulatory pressure, there are significant differences in the coping strategies of different firms [107]. This suggests that managers' green perception plays a crucial role in the relationship between environmental regulations and firm performance in the green transformation, which directly affects firms' daily operations and long-term development [98,108]. When faced with environmental administrative supervision, green risk perception drives managers to develop green innovation strategies such as upgrading production technology and purchasing clean energy to avoid the risk of illegal and political risks, while green benefit perception drives managers to implement green technology innovations to maintain good corporate relations [109]. In the face of environmental economic regulation, green risk perception leads managers to invest more in green research and development, and increase environmental investments to obtain government environmental subsidies and tax incentives, thus reducing the risk of financing constraints faced by the company, while green benefit perception leads managers to actively develop green products or build green brands to gain a competitive advantage in the market [110]. When faced with environmental soft constraint, green risk perception and green benefit perception motivate managers to disclose social responsibility reports and obtain environmental management system certification to build a corporate image and gain an environmentally friendly reputation [111]. Therefore, the following hypotheses are proposed.

H4a. Managers' green perception positively mediates between environmental administrative supervision and the green transformation of manufacturing enterprises.

H4b. Managers' green perception positively mediates between environmental economic regulation and the green transformation of manufacturing enterprises.

H4c. Managers' green perception positively mediates between environmental soft constraint and the green transformation of manufacturing enterprises.

The hypotheses of this study are shown in Fig. 1.

Table 1
Evaluation system for green transformation of manufacturing enterprises.

Preliminary evaluation indicators	Secondary evaluation index	Index definition	Scoring Criteria
Green system (5 points)	Green concept	Availability of environmental concepts	Yes, 1 point; No, 0 points
	Environmental protection management system	Whether an environmental protection management system is in place	Yes, 1 point; No, 0 points
	Environmental protection emergency mechanism	Whether an environmental incident response mechanism is in place	Yes, 1 point; No, 0 points
	Honourable mention	Whether to obtain awards or honorary titles for energy conservation, emission reduction, environmental protection, etc.	Yes, 1 point; No, 0 points
	Environmental training	Whether education and training related to energy conservation and emission reduction, environmental management and operation are carried out	Yes, 1 point; No, 0 points
Green operation (4 points)	Green supply chain	Whether environmental assessments are carried out on suppliers	Yes, 1 point; No, 0 points
	Green production	Implement cleaner production	Qualitative description, 1 point; Quantitative description, 2 points; None, 0 points
	"Three Simultaneities" system	Whether the "three simultaneous" system is implemented	Yes, 1 point; No, 0 points
Green governance (11 points)	Investment in environmental protection and energy conservation projects	Investment in environmental protection and energy conservation projects	Qualitative description, 1 point; Quantitative description, 2 points; None, 0 points
	Technology research and development	Whether to develop environmental protection and energy-saving technologies	Yes, 1 point; No, 0 points
	The "Three Wastes" are discharged up to standard (waste water, waste gas and solid waste)	Whether the "three waste" indicators meet the emission standards	All reached the standard, 3 points; 2, 2 points; 1 item, 1 point; None, 0 points
	Energy-saving effect	Energy saving type	Save 1 species, 1 point; Save 2 or more, 2 points
	Emission reduction effect	Reduction the number of sewage types	Reduce 1 species, 1 point; Reduced by 2 or more, 2 points
	Resource recovery	Whether to carry out resource recovery activities	Yes, 1 point; No, 0 points
Green responsibility (2 points)	Environmental emergencies or violations	Whether environmental accidents or violations have occurred	Yes, 1 point; No, 0 points
	Green public welfare	Participation in social activities and donations related to the environment	Yes, 1 point; No, 0 points

4. Research design

After theoretical analysis of the relationship among heterogeneous environmental regulations, the green transformation of manufacturing enterprises and managers' green perception, this study further tests the research hypothesis by designing empirical models.

4.1. Sample and data

This study selects manufacturing enterprises listed in Shanghai and Shenzhen A-shares in China from 2015 to 2021 as the research sample, excluding enterprises listed in 2015 and later, ST and PT enterprises and enterprises with a severe lack of research data, and finally obtaining balanced panel data from 802 enterprises with 5754 observations. Information related to the green transformation of manufacturing enterprises was obtained from company annual reports, sustainability reports, and environmental reports. Data on environmental administrative supervision and environmental economic regulation were obtained from the China Environmental Statistics Yearbook and the Global Statistics/Analysis Platform (EPS), data on managers' green perception were obtained from the Financial Text Data Platform (Wingo), and the rest of the data were obtained from the China Securities Market and Accounting Research Database (CSMAR). To avoid the influence of extreme values on the empirical results, all continuous variables were subjected to a bilateral 1% tail shrinkage. The data processing was done through Stata15.0 software.

4.2. Variable measurement

4.2.1. Dependent variable: the green transformation degree of manufacturing enterprises (lnSCORE)

Most of the existing researches are based on the output perspective, using the single indicator of enterprise green total factor productivity to measure [60,61], needing a deeper understanding of the critical element of the whole process in the green transformation of the manufacturing industry. Therefore, drawing on the existing research and combining the objective requirements of green development in the manufacturing industry under "Double Carbon" target and the characteristics of the industry itself, this study constructs an evaluation system for the green transformation degree of manufacturing enterprises from the four dimensions: green system, green operation, green governance and green responsibility. The specific evaluation criteria and descriptions are shown in Table 1, and the natural logarithm of the score of the green transformation system measures the green transformation. The natural logarithm of the evaluation system score is used to measure the green transformation of Chinese manufacturing enterprises [112].

4.2.2. Independent variable: heterogeneous environmental regulations (ER)

This study measures environmental regulations from three aspects: environmental administrative supervision, environmental economic regulation and environmental soft constraint. According to the research of Zhang et al. (2021) [113], we measure environmental administrative supervision (ER1) by the ratio of sulfur dioxide emissions to GDP in the place where the enterprise is registered. The smaller the value, the better the effect of environmental administrative supervision. According to the research of Ying and Zhou (2006) [114], we measure environmental economic regulation (ER2) by the ratio of investment in urban environmental infrastructure construction to industrial added value. The greater the value, the better the effect of environmental economic regulation. According to the research of Yang et al. (2022) [115], we measure environmental soft constraint (ER3) by whether the enterprise has passed the ISO14001 environmental management system certification. The larger the value, the better the effect of environmental soft constraint.

Table 2
Variable definitions.

Type	Name	Symbol	Definition
Dependent variable	Green transformation of manufacturing enterprises	lnSCORE	Natural Logarithm of the Score of the Green Transformation Evaluation System of Manufacturing Enterprises
Independent variable	Environmental administrative supervision	ER1	Sulfur dioxide emissions/GDP in the province where the business is registered
	Environmental economic regulation	ER2	Investment in urban environmental infrastructure/industrial value added
	Environmental soft constraint	ER3	Whether the ISO14001 environmental management system certification. Yes for 1; No for 0
Mediator variable	Managers' green perception	EGP	Frequency of keywords in the green perception measurement dimension of managers' annual reports as a percentage of the total word frequency of the text
Control variable	Scale	SIZE	Natural logarithm of total assets at the end of the period
	Liquidity ratio	LR	Current assets/current liabilities
	Revenue growth rate	SALE	Annual revenue growth rate
	Operating profit margin	OP	Operating profit/revenue
	Receivable turnover rate	AR	Natural logarithm of the number of Directors for the Year
	Age of business	AGE	Year of establishment up to sample year
	Combination of two duties	DUAL	If the chairman and the general manager are the same person, it is 1; otherwise, it is 0
	Four major audits	BIG4	Is 1 for the four largest audits, otherwise it is 0

4.2.3. Mediating variable: managers' green perception (EGP)

According to the research of Wu and Bi (2013) [116], a series of keywords related to ecology and environment, such as "environmental protection, ecology, low carbon, environment, green, clean, purification, pollution, treatment, waste gas, wastewater", were selected from the annual reports of enterprises using the text analysis method, and extracted from the Wingo database. The frequency of keywords in the "Management Discussion" section of the annual report was extracted from the Wingo database, and the ratio of the frequency of keywords to the total frequency of words in the text was calculated to measure managers' green perception.

4.2.4. Control variables

According to the research of Dai and Yang (2022) [66], the size of the enterprise (SIZE), liquidity ratio (LR), operating profit margin (OP), revenue growth rate (SALE), accounts receivable turnover (AR), dual employment (DUAL), age of the enterprise (AGE), and whether it is a Big 4 audit (BIG4) were selected as the control variables. Specific variables are defined in Table 2.

4.3. Statistical analysis

The results of the descriptive statistics of the main variables are shown in Table 3. The mean value of green transformation of manufacturing enterprises is 2.124, with a standard deviation of 0.569, indicating that under "Double Carbon" target, some Chinese manufacturing enterprises have actively implemented the low-carbon development concept and achieved specific results. However, the overall transformation level needs to be strengthened. There are significant differences, which is consistent with the fact that China is currently in the initial " Double Carbon" strategy stage. The mean value of environmental administrative supervision is 5.959, the mean value of environmental economic regulation is 0.027, and the mean value of environmental soft constraint is 0.313, indicating that China currently relies mainly on administrative regulation to implement environmental regulations, while market regulation and soft constraint are still in their infancy. The overall situation of environmental regulations is one of emphasis on coercion rather than incentives. The mean value of managers' green perception is 0.008, indicating that the subjective cognition of managers of Chinese manufacturing enterprises towards the ecological environment is still weak, revealing the intrinsic reasons for the poor level of green transformation of Chinese manufacturing enterprises.

4.4. Methodology

Based on the proposed research hypotheses and variable definitions, this study empirically tests the research hypotheses using a Hausman fixed-effects model with panel data to effectively avoid the endogeneity effects of individual differences on the empirical results [117]. Further, according the study of Wen et al. (2005), this study uses stepwise analysis to construct a mediating effect test model, which aims to test the mechanism of heterogeneous environmental regulations and the green transformation of manufacturing enterprises [118]. The specific models are as follows.

$$lnSCORE_{i,t} = \alpha_0 + \alpha_1 ER_t + \sum \alpha_2 CVs_{i,t} + \sum industry + \sum year + \varepsilon_{i,t}$$

$$EGP_{i,t} = \beta_0 + \beta_1 ER_t + \sum \beta_2 CVs_{i,t} + \sum industry + \sum year + \varepsilon_{i,t}$$

$$lnSCORE_{i,t} = \gamma_0 + \gamma_1 EGP_{i,t} + \sum \gamma_2 CVs_{i,t} + \sum industry + \sum year + \varepsilon_{i,t}$$

$$lnSCORE_{i,t} = \delta_0 + \delta_1 ER_t + \delta_2 EGP_{i,t} + \sum \delta_3 CVs_{i,t} + \sum industry + \sum year + \varepsilon_{i,t}$$

$lnSCORE_{i,t}$ indicates the comprehensive score of green transformation of Enterprise i in Period t; ER_t indicates the heterogeneity of environmental regulation in Period t, the empirical analysis substitutes the environmental administrative supervision (ER1), envi-

Table 3
Descriptive statistics.

Variables	Observed value	Average value	Medium value	Minimum value	Maximum value	Standard deviation
lnSCORE	5754	2.124	2.197	0.693	2.996	0.569
ER1	5754	5.959	2.946	0.026	40.785	7.671
ER2	5754	0.027	0.015	0.002	0.162	0.036
ER3	5754	0.313	0.000	0.000	1.000	0.464
EGP	5754	0.008	0.004	−0.355	0.336	0.015
LR	5754	2.259	1.700	0.511	10.961	1.764
SALE	5754	0.229	0.123	−0.625	2.422	0.459
OP	5754	0.066	0.066	−0.624	0.448	0.140
AR	5754	13.400	4.359	0.847	281.387	36.613
SIZE	5754	22.488	22.311	20.352	26.010	1.177
DUAL	5754	0.285	0.000	0.000	1.000	0.452
AGE	5754	19.152	19.000	8.000	33.000	5.133
BIG4	5754	0.0610	0.000	0.000	1.000	0.239

Table 4
Correlation and multicollinearity test of main variables.

Variables	lnSCORE	ER1	ER2	ER3	EGP2	SIZE	GROWTH	BSIZE	DUAL	AGE	LR	BIG4	OP	VIF
lnSCORE	1.000													
ER1	−0.067***	1.000												1.07
ER2	0.068***	−0.141***	1.000											1.05
ER3	0.251***	−0.026**	−0.050***	1.000										1.02
EGP	0.152***	−0.001	0.020	0.065***	1.000									1.03
SIZE	−0.205***	−0.027**	0.041***	−0.029**	−0.083***	1.000								1.27
GROWTH	−0.115***	0.045***	0.056***	−0.025*	0.012	0.037***	1.000							1.03
BSIZE	0.084***	−0.014	−0.005	0.018	−0.016	0.245***	0.011	1.000						1.10
DUAL	0.143***	0.086***	−0.036***	0.013	0.049***	−0.043***	−0.123***	0.058***	1.000					1.07
AGE	0.512***	−0.009	0.096***	0.059***	0.115***	−0.363***	−0.055***	0.068***	0.166***	1.000				1.48
LR	−0.137***	−0.102***	−0.011	−0.042***	−0.077***	0.061***	−0.008	−0.004	−0.070***	−0.131***	1.000			1.04
BIG4	0.240***	−0.136***	−0.021	0.076***	0.054***	−0.077***	−0.077***	−0.014	0.111***	0.152***	−0.045***	1.000		1.07
OP	0.207***	−0.030**	0.040***	0.016	0.005	−0.111***	−0.026**	0.022	0.061***	0.388***	−0.053***	0.058***	1.000	1.18

Note: * * *, * *, and * are significant levels of 1%, 5%, and 10% respectively, from now on.

ronmental economic regulation (ER2) and environmental soft constraint (ER3) into the regression model respectively; $EGP_{i,t}$ is the managers' green perception of Enterprise i in Period t; $CVs_{i,t}$ represents control variables; $\sum industry$ and $\sum year$ are used to estimate and control industry and year fixed effects; $\varepsilon_{i,t}$ denotes the random disturbance term. If Hypothesis1, Hypothesis2, Hypothesis 3 and Hypothesis 4 hold, then α_1, β_1, γ_1 and δ_1 in the models are all significantly positive.

5. Results

According to the research models designed in the above section, we empirically test the research hypotheses proposed in this study through correlation and multicollinearity test, benchmark regression test and robustness test.

5.1. Correlation and multicollinearity tests

The correlation and multicollinearity test results of the main variables in this study are shown in Table 4. The correlation of the main variables can preliminarily verify the research hypothesis in this study, and the VIF values of the relevant variables are all less than 10, indicating that there is no serious multicollinearity among the variables.

5.2. Baseline results

The results of the benchmark regression between heterogeneous environmental regulations and the green transformation of manufacturing firms are shown in Table 5. As can be seen from column (1), after controlling for industry-fixed and year-fixed effects, the regression coefficient between environmental administrative supervision and green transformation of manufacturing enterprises is significantly negative at the 1% level, i.e., for every 1% strengthening of environmental administrative supervision, the level of green transformation of manufacturing enterprises can be increased by 0.28% accordingly, and Hypothesis 1a is verified. It indicates that Chinese Government has effectively urged manufacturing enterprises to increase their attention to and practice environmental protection in their daily operation and production process through environmental administrative supervision, which has achieved an increase in the level of green transformation of enterprises. From column (2), the regression coefficient between environmental economic regulation and green transformation of manufacturing enterprises is significantly positive at the 5% level, i.e., for every 1% strengthening of environmental economic regulation, the level of green transformation of manufacturing enterprises can be increased by 38.68%, and Hypothesis 1b is verified. It shows that environmental economic regulation can create a good market environment for green development and guide enterprises to implement green development strategies proactively, thus improving the level of green transformation. As shown in column (3), the regression coefficient between environmental soft constraint and green transformation of

Table 5
Regression results of heterogeneous environmental regulations and green transformation of manufacturing enterprises.

Variables	(1)	(2)	(3)
	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0028***		
	(−2.6290)		
ER2		0.3868**	
		(2.4518)	
ER3			0.2651***
			(21.9278)
LR	−0.0171***	−0.0177***	−0.0169***
	(−4.5929)	(−4.7366)	(−4.7498)
SALE	−0.0130	−0.0166	−0.0093
	(−0.9549)	(−1.2197)	(−0.7055)
OP	0.1734***	0.1844***	0.1473***
	(4.1322)	(4.3856)	(3.6855)
AR	−0.0004*	−0.0004*	−0.0004**
	(−1.9357)	(−1.9543)	(−2.3196)
SIZE	0.1977***	0.1954***	0.1939***
	(34.3406)	(33.6063)	(34.5427)
DUAL	−0.0675***	−0.0640***	−0.0530***
	(−5.2577)	(−5.0146)	(−4.3228)
AGE	0.0114***	0.0114***	0.0096***
	(9.3288)	(9.2706)	(8.1481)
BIG4	0.0744***	0.0801***	0.0816***
	(3.4083)	(3.6840)	(3.8401)
_cons	−2.3782***	−2.3770***	−2.2924***
	(−7.4811)	(−7.2953)	(−7.2172)
Industry	control	control	control
Year	control	control	control
N	5754	5754	5754
r2_a	0.4334	0.4329	0.4876

Table 6

Robustness test results.

Variables	Replace the dependent variable			Control omitted variable			Change the sample size		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	SCORE1	SCORE1	SCORE1	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0010**			−0.0025**			−0.0026**		
	(-2.4164)			(-2.3376)			(-2.3654)		
ER2		0.1375**			0.4344***			0.4206**	
		(2.2721)			(2.7246)			(2.4787)	
ER3			0.1096***			0.2591***			0.2669***
			(23.1803)			(21.2930)			(20.2417)
LEV				−0.1759***	−0.1832***	−0.1898***			
				(-3.0467)	(-3.1722)	(-3.4492)			
ROA				0.9071***	0.9316***	0.6819***			
				(4.3659)	(4.4758)	(3.3997)			
TobinQ				0.0013	0.0015	0.0063			
				(0.2299)	(0.2590)	(1.1521)			
TOP10				−0.0013***	−0.0012***	−0.0009**			
				(-2.7032)	(-2.5880)	(-1.9952)			
_cons	−1.4032***	−1.4026***	−1.3662***	−2.2977***	−2.2927***	−2.3247***	−2.4335***	−2.4264***	−2.3228***
	(-8.1292)	(-7.9924)	(-7.9284)	(-7.1327)	(-6.9413)	(-7.1403)	(-7.4302)	(-7.2372)	(-7.1181)
Controls	control	control	control	control	control	control	control	control	control
Industry	control	control	control	control	control	control	control	control	control
Year	control	control	control	control	control	control	control	control	control
N	5754	5754	5754	5754	5754	5754	5754	5754	5754
r2_a	0.4524	0.4522	0.5150	0.4457	0.4457	0.4880	0.4456	0.4455	0.4891

manufacturing enterprises is significantly positive at the 1% level, i.e., for every 1% strengthening of environmental soft constraint, the level of green transformation of manufacturing enterprises can be increased by 26.51% accordingly, Hypothesis 1c is verified. It indicates that with the concept of green development gradually gaining popularity, the behavior and effect of enterprises' emissions have been highly concerned by all sectors, effectively promoting enterprises to actively carry out energy saving and emission reduction activities and improve their green transformation level.

In contrast to existing studies, this study further compares the differences in the effects of three environmental regulation tools on the green transformation of manufacturing industries [119,120]. The regression coefficients of the three environmental regulation tools show that environmental economic regulation is the most effective in promoting the green transformation of manufacturing enterprises, followed by environmental soft constraint and environmental administrative supervision. It reflects the fact that the traditional high mandatory environmental administrative regulation ignores the difference in the cost of green transformation of manufacturing enterprises in the process of implementation, which results in the enterprises being forced to fulfill the government's green transformation requirements under the "one-size-fits-all" environmental regulations system without improving their motivation for green transformation. Environmental economic regulation and environmental soft constraint, on the other hand, provide considerable freedom for manufacturing enterprises to create environmental benefits while improving their economic efficiency by participating in market-based transactions or building new linkages with stakeholders, thereby increasing their initiative to green transformation.

5.3. Robustness test results

To ensure the reliability of the above empirical results, this study uses the following methods to test the robustness. Firstly, replacing the dependent variable with the ratio of manufacturing enterprises' green transformation score to total score (SCORE 1). Secondly, controlling for omitted variables, adding the asset-liability ratio (LEV), asset return rate (ROA), TOP10 shareholders' shareholdings (Top 10) and TobinQ value (Tobin Q) into the empirical model to avoid the omission of important influencing factors. Thirdly, excluding the sample in 2018 to avoid interference considering that China has implemented the Environmental Protection Tax Law since 2018, which will replace the emission fees levied on enterprises with environmental protection taxes. The results of the robustness tests are shown in Table 6, from which it can be seen that the empirical results of this study still hold after a series of robustness tests.

6. Further analysis

After verifying the role of heterogeneous environmental regulation in promoting the green transformation of manufacturing enterprises, this section further examines whether managers' green perception plays an intermediary role between heterogeneous environmental regulation and the green transformation of manufacturing enterprises. In addition, we also verify the heterogeneous influence of environmental policy uncertainty, property rights, and regions on heterogeneous environmental regulation and green transformation of manufacturing enterprises.

6.1. Mechanism analysis

The regression results of the mediating effect of managers' green perception between heterogeneous environmental regulation and green transformation of manufacturing enterprises are shown in Table 7. The results in columns (1) to (3) show that after controlling for industry-fixed and year-fixed effects, the regression coefficient of environmental administrative supervision and managers' green perception are significantly negative at the level of 5%. In comparison, the regression coefficients of environmental economic

Table 7
Regression results of mediating effects of managers' green perception.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	EGP	EGP	EGP	lnSCORE	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0001**				−0.0027**		
	(−2.3956)				(−2.4931)		
ER2		0.0112**				0.3634**	
		(2.4016)				(2.3051)	
ER3			0.0018***				0.2622***
			(3.8734)				(21.6372)
EGP				2.1175***	2.0872***	2.0935***	1.6523***
				(5.8151)	(5.7303)	(5.7430)	(4.6431)
_cons	−0.0221***	−0.0220***	−0.0220***	−2.3541***	−2.3321***	−2.3310***	−2.2561***
	(−3.8765)	(−3.9549)	(−3.8376)	(−7.2002)	(−7.2394)	(−7.0706)	(−7.0307)
Controls	control	control	control	control	control	control	control
Industry	control	control	control	control	control	control	control
Year	control	control	control	control	control	control	control
N	5754	5754	5754	5754	5754	5754	5754
r2_a	0.0696	0.0695	0.0717	0.4466	0.4472	0.4470	0.4899

regulation, environmental soft constraint and managers' green perception are significantly positive at the level of 5% and 1%, indicating that all three environmental regulation tools are effective in improving managers' green perception. Hypothesis 2a, Hypothesis 2b and Hypothesis 2c are all verified. The results in column (4) show that the regression coefficient between managers' green perception and manufacturing enterprises' green transformation is significantly positive at 1%, indicating that managers' green perception can effectively promote manufacturing enterprises' green transformation. Hypothesis 3 is verified. The results in columns (5) to (7) show that the regression coefficient between environmental administrative supervision and green transformation of manufacturing enterprises is significantly negative at the level of 5%, indicating that the manager's green perception plays a partial mediating effect between environmental administrative supervision and green transformation of manufacturing enterprises, accounting for 7.56%, Hypothesis 4a is verified. The regression coefficient between environmental economic regulation and green transformation of manufacturing enterprises is significantly positive at the level of 5%, indicating that the manager's green perception plays a partial mediating effect between environmental economic regulation and green transformation of manufacturing enterprises, accounting for 6.13%, Hypothesis 4b is verified. The regression coefficient between environmental soft constraint and green transformation of manufacturing enterprises is significantly positive at the level of 1%, indicating that managers' green perception plays a partial mediating effect between environmental soft constraint and green transformation of manufacturing enterprises, accounting for 1.44%, Hypothesis 4c is verified.

All three environmental regulation tools can promote the green transformation of manufacturing enterprises by enhancing managers' green perception. Further comparing the differences in the effects of managers' green perception among the three environmental regulation tools, it can be seen that managers' green perception plays the most significant mediating role in environmental administrative supervision, followed by environmental economic regulation and environmental soft constraint. It shows that under the incentive of environmental economic regulation, managers can grasp the development opportunities in the process of green market trading of emission rights and carbon emission rights, so that they can proactively improve their green awareness and carry out green transformation measures to improve the level of green transformation of enterprises vigorously. Under the pressure of environmental administrative supervision, the managers of enterprises are often forced to pay more attention to the ecological environment and enhance their awareness of it. They would promote the green transformation of manufacturing enterprises by a series of environmental management measures, such as increasing green research and development investment and expanding environmental protection investment. However, there is an overall lack of initiative, and the green measures may have a perfunctory motive of "putting on a show", resulting in a weak substantive effect of the green transformation of enterprises. Under the guidance of environmental soft constraint, enterprises can implement a series of green transformation measures in line with the changes in the external environment. However, the effect on the enhancement of managers' green cognitive ability is also relatively weak due to the low level of regulation.

6.2. Heterogeneity analysis

It has been shown that heterogeneous environmental regulations can significantly contribute to the green transformation of manufacturing enterprises. Moreover, the existing literature provide a more comprehensive empirical examination of the factors influencing heterogeneous environmental regulations but lack comprehensiveness [121–123]. Therefore, this study further discusses the heterogeneous impacts of environmental policy uncertainty, property rights, and regions on the relationship between environmental regulations and the green transformation of manufacturing enterprises.

6.2.1. Heterogeneity analysis based on policy uncertainty

The government occupies a central and irreplaceable position in the implementation of environmental regulations. Similarly, local environmental officials, as implementers of environmental regulation policies, also have a significant impact on the effectiveness of the

Table 8
Results of heterogeneity analysis of environmental policy uncertainty.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	High policy uncertainty	Low policy uncertainty	High policy uncertainty	Low policy uncertainty	High policy uncertainty	Low policy uncertainty
	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0045***	−0.0018				
	(-2.9385)	(-1.1404)				
ER2			0.4945***	0.3629		
			(2.7700)	(0.7711)		
ER3					0.2706***	0.2619***
					(17.6590)	(13.2469)
_cons	−2.3152***	−2.6502***	−2.3173***	−2.6934***	−2.2700***	−2.5743***
	(-6.9693)	(-11.2630)	(-6.7505)	(-11.5410)	(-6.8060)	(-11.2933)
Controls	control	control	control	control	control	control
Industry	control	control	control	control	control	control
Year	control	control	control	control	control	control
N	3611	2143	3611	2143	3611	2143
r2_a	0.4527	0.4101	0.4512	0.4103	0.5051	0.4627

green transformation of enterprises [124]. Under China's political system and official promotion system, the policy uncertainty generated by the change of environmental officials can significantly impact enterprises' green transformation [125]. Therefore, drawing on the study by Wan et al. (2021) [70], the dummy variable of change in the head of the regional ecological and environmental department or the head of the ecological and environmental bureau was used as a proxy for regional policy uncertainty, to test the difference in the effect of policy uncertainty on the relationship between heterogeneous environmental regulations and the green transformation of manufacturing enterprises. The results are shown in Table 8. As can be seen from the table, the regression coefficient between environmental administrative supervision and green transformation of manufacturing enterprises under high policy uncertainty is significantly negative at the 1% level. In contrast, the regression coefficient between environmental administrative regulation and green transformation of manufacturing enterprises under low policy uncertainty does not pass the significance test, indicating that policy uncertainty can play a positive moderating role between environmental administrative supervision and green transformation of manufacturing enterprises. The coefficient of regression between environmental economic regulation and green transformation of manufacturing enterprises under high policy uncertainty is significantly positive at the 5% level. In contrast, the coefficient of regression between environmental economic regulation and green transformation of manufacturing enterprises under low policy uncertainty does not pass the significance test, indicating that policy uncertainty can play a positive moderating role between environmental economic regulation and green transformation of manufacturing enterprises. Environmental soft constraint can significantly enhance the green transformation of manufacturing enterprises regardless of the level of policy uncertainty. In summary, heterogeneous environmental regulations are generally more effective in regions with high policy uncertainty, suggesting that on the one hand, the existence of policy uncertainty can effectively exert a "constraint effect" prompting enterprises to pay more attention to environmental management; on the other hand, it can effectively exert an "incentive effect", motivating enterprises to make a green transition.

6.2.2. Heterogeneity analysis based on the property rights

The sample enterprises are grouped according to the nature of enterprise property rights, and then regression analysis was conducted to test whether there were differences in the impact of heterogeneous environmental regulations on the green transformation of manufacturing enterprises under different property rights. The empirical results are shown in Table 9. As can be seen from the table, environmental regulations as a whole can play a more pronounced role in the green transformation of state-owned manufacturing enterprises, with environmental economic regulation having the most significant effect, followed by environmental administrative supervision. In contrast, the effect of environmental soft constraint on the promotion of green transformation of manufacturing enterprises is not affected by the nature of property rights. The possible reason for this is that compared to non-state enterprises, state-owned enterprises not only need to focus on improving their economic efficiency but also need to take on more social responsibility. In addition, state-owned enterprises can receive more support from the government in the process of green transformation, and thus have a better risk-taking ability. Therefore, compared to non-SOEs, SOEs are more responsive to national green policies.

6.2.3. Heterogeneity analysis based on regions

The sample enterprises were divided into different regions and then grouped into regression analyses, to test whether there were differences in the effects of heterogeneous environmental regulations on the green transformation of manufacturing enterprises within different regions. The empirical results are shown in Table 10. As can be seen from the table, the effect of environmental administrative supervision and environmental economic regulation on the green transformation of manufacturing enterprises is only effective in the eastern region but not in the central and western regions. This phenomenon is inextricably linked to the economic development level, industrial configuration and administrative capacity of the eastern region is ahead of other regions in China. Compared to other regions of China, enterprises in the eastern region face more stringent environmental administrative supervision, and are forced to pay more

Table 9
Results of heterogeneity analysis of property rights.

Variables	(1)	(2)	(3)	(4)	(5)	(6)
	State-owned enterprises	Non-state-owned enterprises	State-owned enterprises	Non-state-owned enterprises	State-owned enterprises	Non-state-owned enterprises
	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0068***	−0.0021				
	(-4.6500)	(-1.4032)				
ER2			0.7409***	−0.0063		
			(3.0413)	(-0.0324)		
ER3					0.2216***	0.2872***
					(11.5391)	(18.8100)
_cons	−2.1371***	−2.5699***	−2.2490***	−2.5907***	−2.2715***	−2.4028***
	(-9.4345)	(-7.8318)	(-9.8688)	(-7.8354)	(-10.4833)	(-7.3900)
Controls	control	control	control	control	control	control
Industry	control	control	control	control	control	control
Year	control	control	control	control	control	control
N	1836	3918	1836	3918	1836	3918
r2_a	0.4289	0.4280	0.4233	0.4277	0.4592	0.4799

Table 10
Analysis results of regional heterogeneity of enterprises.

Variables		East				Middle			West	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE	lnSCORE
ER1	−0.0072***			0.0015			0.0026		
	(-3.7811)			(0.5534)			(0.8966)		
ER2		0.4183**			1.7936			1.7202	
		(2.5700)			(1.1652)			(0.9433)	
ER3			0.2626***			0.3251***			0.2160***
			(18.8329)			(9.9077)			(5.9403)
_cons	−2.0862***	−2.1190***	−2.1311***	−2.0328***	−2.0530***	−1.5396***	−2.2970***	−2.3129***	−2.1753***
	(-12.1353)	(-12.3633)	(-13.0350)	(-4.9268)	(-5.0183)	(-4.0315)	(-5.4946)	(-5.5482)	(-5.5536)
Controls	control	control	control	control	control	control	control	control	control
Industry	control	control	control	control	control	control	control	control	control
Year	control	control	control	control	control	control	control	control	control
N	3120	3120	3120	610	610	610	380	380	380
r2_a	0.4539	0.4516	0.5060	0.4087	0.4064	0.4808	0.5872	0.5860	0.6260

attention to their green transformation due to the legality requirements. In addition, the eastern region has a more developed green trading market, more financial and taxation policies to help enterprises to save energy and reduce emissions. Therefore, enterprises in the eastern region are more motivated to implement green transformation. There is no significant difference in the effect of environmental soft constraint on the green transformation of manufacturing enterprises in the eastern, central or western regions, indicating that China has achieved significant results in the promotion of ecological environment concept. Enterprises can actively participate in environmental governance under the guidance of the government and the public, thus improving their green transformation level.

7. Conclusion, policy implications, and limitations

7.1. Conclusions

This study selects Chinese listed manufacturing enterprises from 2015 to 2021 as the sample to explore the differences in the effects between heterogeneous environmental regulations and the green transformation of manufacturing enterprises. Moreover, this study explores the response mechanisms of manufacturing enterprises to achieve green transformation under heterogeneous environmental regulations from the perspective of managers' green perception. Further, this study identifies the differences in their effects from the perspectives of heterogeneity such as policy uncertainty, property rights and regions. This study has three main conclusions. First, environmental administrative supervision, environmental economic regulation, and environmental soft constraint can all promote the green transformation of manufacturing enterprises, but their effects are obviously different. Specifically, environmental economic regulation is the most effective, followed by environmental soft constraint and environmental administrative supervision. This finding is still valid after a series of robustness tests, which makes up for the lack of the existing literature by comparing the different effects of heterogeneous environmental regulation tools [126]. Second, in terms of mechanism of action, managers' green perception, as an internal driver of green transformation, partially mediates the relationship between heterogeneous environmental regulations and the green transformation of manufacturing enterprises. Among three environmental regulations, managers' green perception plays the most significant mediating effect on environmental administrative supervision, followed by environmental economic regulation and environmental soft constraint. This finding makes up for the lack of the existing literature by exploring the driving factors of green transformation of manufacturing enterprises from an internal perspective [59]. Third, from the perspective of heterogeneity of impacts, the promotion effect of environmental administrative supervision and environmental economic regulation on green transformation is more evident among enterprises with high environmental policy uncertainty, state-owned and eastern regions, while all enterprises involved in environmental soft constraint can show a positive willingness to green transformation, which further enriches the discussion on the heterogeneous influencing factors of green transformation of manufacturing enterprises [127].

7.2. Policy implications

The findings of this study help to explore the differences in the impact of heterogeneous environmental regulations on the green transformation of manufacturing enterprises and the response mechanisms within the enterprises. Further, based on the policy recommendations provided by existing studies [128,129], this study proposes the following recommendations for Chinese government to develop heterogeneous environmental regulations for the implementation of "Double Carbon" target.

Firstly, improve the monitoring system of carbon emission levels of manufacturing enterprises. When implementing policies related to environmental administrative supervision, Chinese government should directly link the assessment criteria of enterprises' green transformation with their historical carbon emission levels. Also, Chinese government needs to fully consider the differences in carbon emission pressure and costs of green transformation among different enterprises, breaking the barrier of enterprises' thinking of passively meeting the legality requirements of the government, which can actively mobilize enterprises' enthusiasm for green transformation.

Secondly, improve the market trading system for emission and carbon emission rights. When implementing policies related to environmental economic regulation, Chinese government should take the level of green perception of trading subjects as an evaluation criterion for the entry threshold of the trading market. At the same time, Chinese government should strengthen the joint learning mechanism between the government and enterprises, urging enterprises' managers to keep abreast of the latest developments of "Double Carbon" strategy and environmental policies to help manufacturing enterprises achieve healthy and sustainable development.

Thirdly, strengthen green and low-carbon education for all citizens. When implementing policies related to soft environmental constraint, Chinese government should focus on the diversity of implementation methods and the scientific nature of promotion efforts, constructing an interactive platform for information sharing with low-carbon emission reduction as the core. Also, Chinese government should encourage all citizens to actively exercise their right to environmental regulations to improve the green level of manufacturing enterprises.

Fourthly, formulate differentiated environmental policies based on policy uncertainty, enterprise property rights, and regions. For state-owned enterprises with high environmental policy uncertainty and leading economic development, green governance effects should be incorporated into their assessment systems to encourage them to take the lead in achieving "Double Carbon" target. For non-state-owned enterprises in regions with low environmental policy uncertainty and relatively backward economies, Chinese government should provide more support for their green transformation.

7.3. Limitations

There are two main limitations of this study. Firstly, this study only focuses on listed Chinese manufacturing enterprises, ignoring the level of green transformation of a wide range of unlisted enterprises under heterogeneous environmental regulations and their internal response mechanisms. Secondly, the limited research period of the research subjects has resulted in some of the environmental regulation tools needing to be used to their maximum effect, which may have an impact on the empirical findings.

Author contribution statement

Yongjun Tang: Conceived and designed the experiments; Contributed reagents, Materials, analysis tools and data; Critically revising its important intellectual content. Yuqiu Qi: Performed the experiments; Wrote the paper; Critically revising its important intellectual content. Fen Zhou: Contributed reagents, materials, Analysis tools or data; Wrote the paper; Final approval of the version submitted. Lei Hua: Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data included in article/supplementary material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] B. Jin, The mission and value of industry–theoretical logic of China's industrial transformation and upgrading, China Industrial Economics 318 (9) (2014) 51–64, https://doi.org/10.19581/j.cnki.ciejournal.2014.09.004.

[2] B.Q. Lin, China's high-quality economic growth in the process of carbon neutrality, China Finance and Economic Review 11 (4) (2022) 3–22, https://doi.org/10.1515/CFER-2022-0020.

[3] Y.J. Yuan, Z. Chen, Environmental regulation, green technology innovation and the transformation and upgrading of China's manufacturing industry, Studies in Science of Science 37 (10) (2019) 1902–1911, https://doi.org/10.16192/j.cnki.1003-2053.2019.10.020.

[4] Z.P. Yu, L. Tian, Factor endowment, industrial environment and the quality of China's manufacturing development, Sci. Res. Manag. 41 (12) (2020) 103–111, https://doi.org/10.19571/j.cnki.1000-2995.2020.12.009.

[5] H. Fu, G.P. Li, T. Zhu, Carbon emissions from manufacturing industries in China: decomposition of industry differences and drivers, Reformatio 5 (2020) 38–52.

[6] Y.F. Wang, J. Liu, Z.H. Zhao, J. Ren, X.R. Chen, Research on carbon emission reduction effect of China's regional digital trade under the "double carbon" target– combination of the regulatory role of industrial agglomeration and carbon emissions trading mechanism, J. Clean. Prod. 405 (2023), 137049, https://doi.org/10.1016/j.jclepro.2023.137049.

[7] M. Li, Y. He, J.H. Pan, The "double carbon" target, carbon tax policy and the resilience of China's manufacturing industry chain, China Population, Resour. Environ. 32 (9) (2022) 22–34, https://doi.org/10.12062/cpre.20220530.

[8] N.T. Ching, G. Morteza, I. Mohammad, M. Parisa, A. Shahla, Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development, J. Clean. Prod. 334 (2022), 130133, https://doi.org/10.1016/j.jclepro.2021.130133.

[9] X.M. Xie, Y.H. Han, How can local manufacturing enterprises achieve "magnificent transformation" in green innovation? –A multi-case study based on an attention-based view, Manag. World 38 (3) (2022) 76–106, https://doi.org/10.3969/j.issn.1002-5502.2022.03.006.

[10] H.B. Sun, Z.L. Liu, Environmental regulation, clean technology innovation and green transformation of Chinese industry, Sci. Res. Manag. 42 (11) (2021) 54–61, https://doi.org/10.19571/j.cnki.1000-2995.2021.11.007.

[11] J. Xiao, P. Zeng, G. Ren, How to improve the green transformation performance of manufacturing industry? – A histological study based on TOE framework, Studies in Science of Science 40 (12) (2022) 2162–2172, https://doi.org/10.16192/j.cnki.1003-2053.20220322.001.

[12] S. Wang, H. Wang, Can global value chain participation drive green upgrade in China's manufacturing industry? Int. J. Environ. Res. Publ. Health 19 (19) (2022), 12013 https://doi.org/10.3390/ijerph191912013.

[13] H.W. Gao, B. Wu, The impact of the opening of high-speed rail in Yangtze River Economic Zone on the green transformation of manufacturing industry, China Population, Resour. Environ. 32 (8) (2022) 118–127, https://doi.org/10.12062/cpre.20220407.

[14] B.H. Peng, C.Y. Zheng, G. Wei, E. Ehsan, The cultivation mechanism of green technology innovation in manufacturing industry: from the perspective of ecological niche, J. Clean. Prod. 252 (2020), 119711, https://doi.org/10.1016/j.jclepro.2019.119711.

[15] L. Wei, Y. Zhang, J. Jia, How do environmental taxes affect green process innovation? Evidence from the Chinese manufacturing industry, J. Manuf. Technol. Manag. 4 (2023) 1–10, https://doi.org/10.1108/JMTM-09-2022-0345.

[16] J. Hou, H. Chen, A study on the performance and drivers of green transformation of technological innovation in high patent-intensive manufacturing industries in China, Manag. Rev. 30 (4) (2018) 59–69, https://doi.org/10.14120/j.cnki.cn11-5057/f.2018.04.006.

[17] Y.J. Feng, X. Dong, X.M. Zhao, A.K. Zhu, Evaluation of urban green development transformation process for Chinese cities during 2005–2016, J. Clean. Prod. 266 (2020) 121707, https://doi.org/10.1016/j.jclepro.2020.121707.

[18] Y.T. Lei, J.J. Sun, Can energy-saving consumption incentive policies lead manufacturing enterprises to green transformation? Ind. Econ. Res. 112 (3) (2021) 17–30+56, https://doi.org/10.13269/j.cnki.ier.2021.03.002.

[19] D.B. Zhu, L. Ren, Environmental regulation, foreign direct investment and the green transformation of Chinese industry, Journal of International Trade 11 (2017) 70–81, https://doi.org/10.13510/j.cnki.jit.2017.11.007.

[20] M.E. Porter, D.L.C. Van, Toward a new conception of the environment-competitiveness relationship, J. Econ. Perspect. 9 (4) (1995) 97–118, https://doi.org/10.1257/jep.9.4.97.

[21] F.M. Gollop, M.J. Robert, Environmental regulations and productivity growth: the case of fossil-fueled electric power generation, J. Polit. Econ. 91 (4) (1983) 654–674, https://doi.org/10.2307/1831072.

[22] Y.R. Cao, J. Liu, Y. Yu, G. Wei, Impact of environmental regulation on green growth in China's manufacturing industry–based on the Malmquist-Luenberger index and the system GMM model, Environ. Sci. Pollut. Control Ser. 27 (33) (2020) 41928–41945, https://doi.org/10.1007/s11356-020-10046-1.

[23] X. Peng, B. Li, A study on the green transformation of Chinese industry under different types of environmental regulations, J. Finance Econ. 42 (7) (2016) 134–144, https://doi.org/10.16538/j.cnki.jfe.2016.07.012.

[24] L. Wang, Y. Long, C. Li, Research on the impact mechanism of heterogeneous environmental regulation on enterprise green technology innovation, J. Environ. Manag. 322 (15) (2022), 116127, https://doi.org/10.1016/j.jenvman.2022.116127.

[25] H.M. Wang, Comparison and selection of environmental regulation policy tools in China - an empirical study based on Bayesian model averaging (BMA) approach, China Population, Resour. Environ. 26 (9) (2016) 132–138, https://doi.org/10.3969/j.issn.1002-2104.2016.09.016.

[26] L.H. Yin, X.Q. Meng, C.Q. Wu, The impact of environmental regulation on green total factor productivity of manufacturing industries in the Yangtze River Economic Zone, Reformatio 337 (3) (2022) 101–113.

[27] L.Z. Tang, L. Zhou, M.J. Yang, Environmental regulation and corporate green innovation*: an empirical study based on the "Ten Articles of Atmosphere" policy, Statistical Research 39 (12) (2022) 55–68, https://doi.org/10.19343/j.cnki.11-1302/c.2022.12.004.

[28] Z.Y. Sun, X.P. Wang, C. Liang, F. Cao, L. Wang, The impact of heterogeneous environmental regulation on innovation of high-tech enterprises in China: mediating and interaction effect, Environ. Sci. Pollut. Control Ser. 28 (1) (2021) 1–14, https://doi.org/10.1007/s11356-020-11225-w.

[29] X.J. Xiang, C.J. Liu, M. Yang, Who is financing corporate green innovation? Int. Rev. Econ. Finance 78 (2022) 321–337, https://doi.org/10.1016/j.iref.2021.12.011.

[30] S.Z. Qi, S. Lin, J.B. Cui, Can environmental equity trading market induce green innovation? – Evidence based on data on green patents of listed enterprises in China, Econ. Res. J. 53 (12) (2018) 129–143.

[31] J.H. Liu, H.Y. Wang, H.L.Y.W. Ho, L.C. Huang, Impact of heterogeneous environmental regulation on manufacturing sector green transformation and sustainability, Front. Environ. Sci. 10 (2022), 938509, https://doi.org/10.3389/fenvs.2022.938509.

[32] Y.C. Feng, Y. Geng, Z. Liang, Q. Shen, X.Q. Xia, Research on the impacts of heterogeneous environmental regulations on green productivity in China: the moderating roles of technical change and efficiency change, Int. J. Environ. Res. Publ. Health 18 (21) (2021), 11449, https://doi.org/10.3390/ijerph182111449.

[33] H.L. Li, X.H. Zhu, J.Y. Chen, F.T. Jiang, Environmental regulations, environmental governance efficiency and the green transformation of China's iron and steel enterprises, Ecol. Econ. 165 (2019), 106397, https://doi.org/10.1016/j.ecolecon.2019.106397.

[34] F. Polzin, M. Migendt, F.A. Taeube, P.V. Flotow, Public policy influence on renewable energy investments-A panel data study across OECD countries, Energy Pol. 80 (5) (2015) 98–111, https://doi.org/10.1016/j.enpol.2015.01.026.

[35] R.B. Stewart, Models for environmental regulation: central planning versus market-based approaches, Boston College environmental affairs law review, Boston College. Law School 38 (1) (1992) 547–562.

[36] Y.M. Zhao, F.M. Zhu, L.L. He, The definition, classification and evolution of environmental regulation, China Population, Resour. Environ. 19 (6) (2009) 85–90, https://doi.org/10.3969/j.issn.1002-2104.2009.06.016.

[37] J.M. Zhang, G.Q. Liang, T.W. Feng, C.L. Yuan, W.B. Jiang, Green innovation to respond to environmental regulation: how external knowledge adoption and green absorptive capacity matter? Bus. Strat. Environ. 29 (1) (2019) 39–53, https://doi.org/10.1002/bse.2349.

[38] G.Q. Jose, J.L. Elisenda, Environmental policies and energy efficiency investments, an industry-level analysis, Energy Pol. 156 (9) (2021) 1–9, https://doi.org/10.1016/j.enpol.2021.112461.

[39] R.H. Xie, Y.J. Yuan, J.J. Huang, Different types of environmental regulations and heterogeneous influence on "green" productivity, Evidence from China, Ecol. Econ. 132 (1) (2017) 104–112, https://doi.org/10.1016/j.ecolecon.2016.10.019.

[40] M.L. Cheng, Z. Shao, X.A. Yang, Analysis of coordinated development of energy and environment in China's manufacturing industry under environmental regulation: a comparative study of sub-Industries, Sustainability 11 (22) (2019) 6510, https://doi.org/10.3390/su11226510.

[41] B. Yu, S.Y. Song, J.L. Jiao, R.R. Yan, The impacts of government R&D subsidies on green innovation: evidence from Chinese energy-intensive firms, J. Clean. Prod. 233 (2019) 819–829, https://doi.org/10.1016/j.jclepro.2019.06.107.

[42] F. Xu, Q. Pan, Y.A. Wang, Study on the impact of green and low-carbon transformation on enterprise profitability under the "double carbon" target, Macroeconomics 278 (1) (2022) 161–175, https://doi.org/10.16304/j.cnki.11-3952/f.2022.01.013.

[43] X.S. Li, M. Zhou, C.P. Wang, Local government environmental policy innovation and corporate environmental performance: micro empirical evidence based on the river chief system policy in the Yangtze River Delta, China Population, Resour. Environ. 33 (3) (2023) 77–90.

[44] Q.H. Huang, J.F. Hu, X.D. Chen, Environmental regulation and green total factor productivity: dilemma or win-win?, China Population, Resour. Environ. 28 (11) (2018) 140–149, https://doi.org/10.12062/cpre.20180706.

[45] B.L. Yuan, Q.L. Xiang, Environmental regulation, industrial innovation and green development of Chinese manufacturing: based on an extended CDM model, J. Clean. Prod. 176 (2018) 895–908, https://doi.org/10.1016/j.jclepro.2017.12.034.

[46] H.Q. Wu, S.M. Hu, The impact of synergy effect between government subsidies and slack resources on green technology innovation, J. Clean. Prod. 274 (2020) 1–12, https://doi.org/10.1016/j.jclepro.2020.122682.

[47] L. Xia, S. Gao, J.C. Wei, Q.Y. Ding, Government subsidy and corporate green innovation - does board governance play a role? Energy Pol. 161 (2022) 1–15, https://doi.org/10.1016/j.enpol.2021.112720.

[48] S.L. Qiu, Z.L. Wang, S. Liu, S.Z. Dong, A study on the heterogeneous effect of environmental regulations on environmental performance under non-desired output constraint, China Population, Resour. Environ. 28 (12) (2018) 40–51, https://doi.org/10.12062/cpre.20180719.

[49] W.J. Liu, M.Z. Du, Y. Bai, The impact of environmental regulations on green total factor productivity - a study based on the perspective of technological progress bias, China Population, Resour. Environ. 32 (3) (2022) 95–107, https://doi.org/10.12062/cpre.20211123.

[50] Y.G. Wang, X. Li, Facilitation or disincentive: the impact of government R&D subsidies on firms' green innovation performance, China Industrial Economics 419 (2) (2023) 131–149, https://doi.org/10.19581/j.cnki.ciejournal.2023.02.008.

[51] Y.Y. Ma, X.L. Zhang, Y.T. Sun, Environmental regulations stimulate firms' efforts in R&D? –Empirical evidence from data of thermal power enterprises, Sci. Res. Manag. 39 (2) (2018) 66–74, https://doi.org/10.19571/j.cnki.1000-2995.2018.02.008.

[52] W.H. Li, K.X. Bi, X. Cao, The impact of environmental regulation tools on green technology innovation in manufacturing enterprises - an example of paper and paper product enterprises, Syst. Eng. 31 (10) (2013) 112–122.

[53] W. Yu, Q. Chen, H. Chen, Analysis of the impact of different environmental policy instruments on technological innovation - an empirical study based on provincial panel data in China from 2004 to 2011, Manag. Rev. 28 (1) (2016) 53–61, https://doi.org/10.14120/j.cnki.cn11-5057/f.2016.01.005.

[54] Q.Y. Li, Z.H. Xiao, Heterogeneous environmental regulatory instruments and firms' incentives for green innovation-evidence from listed firms' green patents, Econ. Res. J. 55 (9) (2022) 192–208.

[55] Y.F. Yang, X. Cheng, A study on the impact of environmental regulation tools on corporate green innovation, China Soft Science 1 (2021) 247–252, https://doi.org/10.3969/j.issn.1002-9753.2021.z1.029.

[56] E.T. Graedel, R.B. Allenby, Matrix approaches to abridged life cycle assessment, Environ. Sci. Technol. 29 (3) (1995) 134, https://doi.org/10.1021/es00003a751.

[57] Research Group, Institute of Industrial Economics, Chinese Academy of Social Sciences, P. Li, Research on the green transformation of Chinese industry, China Industrial Economics 4 (2011) 5–14, https://doi.org/10.19581/j.cnki.ciejournal.2011.04.001.

[58] X. Peng, B. Li, Trade openness, FDI and China's industrial green transformation-an empirical study based on dynamic panel threshold model, Journal of International Trade 1 (2015) 166–176, https://doi.org/10.13510/j.cnki.jit.2015.01.016.

[59] W.J. Kong, Research on factors influencing the transformation and upgrading of manufacturing enterprises–an empirical study based on a large sample questionnaire survey of manufacturing enterprises in Zhejiang Province, Manag. World 9 (2012) 120–131, https://doi.org/10.19744/j.cnki.11-1235/f.2012.09.012.

[60] H. Su, L. Zheng, Y.F. Mou, Factor endowment and industrial upgrading in China's manufacturing industry-an analysis based on WIOD and Chinese industrial enterprise database, Manag. World 4 (2017) 70–79, https://doi.org/10.3969/j.issn.1002-5502.2017.04.007.

[61] C. Shen, S.L. Li, L.X. Huang, A study on the mechanism of heterogeneous environmental regulations' impact on China's industrial green transformation - an empirical analysis based on mediating effects, Nankai Econ. Stud. 203 (5) (2018) 95–114, https://doi.org/10.14116/j.nkes.2018.05.006.

[62] H.H. Deng, L.X. Yang, Haze control, local competition and industrial green transformation, China Industrial Economics 10 (2019) 118–136, https://doi.org/10.19581/j.cnki.ciejournal.2019.10.007.

[63] S.L. Yang, B. Yu, S.F. Wang, N.P. Feng, Evaluating the transformation of China's industrial development mode during 2000-2009, Renewable Sustainable Energy Rev. 20 (4) (2013) 585–594, https://doi.org/10.1016/j.rser.2012.12.034.

[64] Y. Rubashkina, M. Galeotti, E. Verdolini, Environmental regulation and competitiveness: empirical evidence on the Porter Hypothesis from European manufacturing sectors, Energy Pol. 83 (8) (2015) 288–300, https://doi.org/10.1016/j.enpol.2015.02.014.

[65] C. Pietrobelli, R. Rabellotti, M. Sanfilippo, Chinese FDI strategy in Italy: the 'Marco Polo' effect, Int. J. Technol. Learn. Innovat. Dev. 4 (4) (2011) 277–291, https://doi.org/10.1504/IJTLID.2011.044138.

[66] X. Dai, S.Z. Yang, Digital empowerment, digital input sources and green transformation of manufacturing industry, China Industrial Economics 9 (2022) 83–101, https://doi.org/10.19581/j.cnki.ciejournal.2022.09.004.

[67] D. Su, B. Sheng, Industrial agglomeration, agglomeration externalities and firm emission reduction - new micro evidence from China, China Economic Quarterly 21 (5) (2021) 1793–1816, https://doi.org/10.13821/j.cnki.ceq.2021.05.14.

[68] C.Y. Qu, J. Shao, Z.H. Cheng, Can embedding in global value chain drive green growth in China's manufacturing industry? J. Clean. Prod. 268 (2020), 121962 https://doi.org/10.1016/j.jclepro.2020.121962.

[69] X.Q. Zhai, Y.F. An, Analyzing influencing factors of green transformation in China's manufacturing industry under environmental regulation: a structural equation model, J. Clean. Prod. 251 (2020), 119760, https://doi.org/10.1016/j.jclepro.2019.119760.

[70] P.B. Wan, G. Yang, L. Chen, How environmental technology standards affect the green transformation of China's manufacturing industry–a perspective based on technological transformation, China Industrial Economics 402 (9) (2021) 118–136, https://doi.org/10.19581/j.cnki.ciejournal.2021.09.006.

[71] D.M. He, P. Liu, Population aging, manufacturing transformation and upgrading and high-quality economic development - based on mediating effect model, Research on Economics and Management 41 (1) (2020) 3–20, https://doi.org/10.13502/j.cnki.issn1000-7636.2020.01.001.

[72] Y. Cao, X. Li, H.L. Hu, G.Y. Wan, S.Y. Wang, How can digitalization drive green transformation in manufacturing enterprises? –An exploratory case study from the perspective of resource orchestration theory, Manag. World 39 (3) (2023) 96–112+126+113, https://doi.org/10.19744/j.cnki.11-1235/f.2023.0045.

[73] H.Y. Deng, G. Bai, Z.Y. Shen, L.Q. Xia, Digital economy and its spatial effect on green productivity gains in manufacturing: evidence from China, J. Clean. Prod. 378 (2022), 134539, https://doi.org/10.1016/j.jclepro.2022.134539.

[74] C. Liu, H.F. Pan, P. Li, Y.X. Feng, Research on the impact and mechanism of digital transformation on green innovation efficiency of manufacturing enterprises, China Soft Science 388 (4) (2023) 121–129, https://doi.org/10.3969/j.issn.1002-9753.2023.04.012.

[75] M. Hamamoto, Environmental regulation and the productivity of Japanese manufacturing industries, Resour. Energy Econ. 28 (4) (2006) 299–312, https://doi.org/10.1016/j.reseneeco.2005.11.001.

[76] Y. Wang, X.H. Sun, The mechanism of the role of government subsidies in driving industrial transformation and upgrading, China Industrial Economics 10 (2017) 99–117, https://doi.org/10.19581/j.cnki.ciejournal.2017.10.007.

[77] J. Hojnik, M. Ruzzier, What drives eco-innovation? A review of an emerging literature, Environ. Innov. Soc. Transit. 19 (2016) 31–41, https://doi.org/10.1016/j.eist.2015.09.006.

[78] Y.J. Tang, P. Li, Board characteristics, environmental regulation and green development of manufacturing Firms - an empirical analysis based on panel data of manufacturing firms from 2012-2016, Econ. Surv. 36 (3) (2019) 73–80, https://doi.org/10.15931/j.cnki.1006-1096.20190416.021.

[79] R.Q. Li, J.S. Zhang, Heterogeneous effects of different types of environmental regulations on local environmental governance, Commercial Research 519 (7) (2020) 36–45, https://doi.org/10.13902/j.cnki.syyj.2020.07.005.

[80] W.J. Du, M.J. Li, Assessing the impact of environmental regulation on pollution abatement and collaborative emissions reduction, Micro-evidence from Chinese industrial enterprises, Environ. Impact Assess. Rev. 82 (5) (2020) 1–10, https://doi.org/10.1016/j.eiar.2020.106382.

[81] D.M. You, Y. Zhang, B.L. Yuan, Environmental regulation and firm eco-innovation: evidence of moderating effects of fiscal decentralization and political competition from listed Chinese industrial enterprises, J. Clean. Prod. 207 (2019) 1072–1083, https://doi.org/10.1016/j.jclepro.2018.10.106.

[82] F. Iraldo, F. Testa, M. Frey, Is an environmental management system able to influence environmental and competitive performance? Management and Audit Scheme (EMAS) in the European Union, J. Clean. Prod. 17 (16) (2009) 1444–1452, https://doi.org/10.1016/j.jclepro.2009.05.013.

[83] L. Wu, X.Y. Jia, C. Wu, J.C. Peng, The impact of heterogeneous environmental regulations on green total factor productivity in China, China Population-Resources and Environment 30 (10) (2020) 82–92, https://doi.org/10.12062/cpre.20200122.

[84] J. Xu, J.B. Cui, Low carbon cities and enterprise green technology innovation, China Industrial Economics 12 (2020) 178–196, https://doi.org/10.19581/j.cnki.ciejournal.2020.12.008.

[85] B.L. Yuan, Y. Zhang, Flexible environmental policy, technological innovation and sustainable development of China's industry: the moderating effect of environment regulatory enforcement, J. Clean. Prod. 243 (2020) 1–17, https://doi.org/10.1016/j.jclepro.2019.118543.

[86] H.P. Huang, Y.F. Xie, Does market-based environmental regulation promote low-carbon industrial transformation? –Evidence from energy-use rights trading, Ind. Econ. Res. 122 (1) (2023) 58–72, https://doi.org/10.13269/j.cnki.ier.2023.01.009.

[87] E. Hille, W. Althammer, H. Diederich, Environmental regulation and innovation in renewable energy technologies: does the policy instrument matter, Technol. Forecast. Soc. Change 153 (4) (2020) 1–22, https://doi.org/10.1016/j.techfore.2020.119921.

[88] D. Fan, X.T. Sun, Environmental regulation, green technology innovation and green economic growth, China Population, Resour. Environ. 30 (6) (2020) 105–115, https://doi.org/10.12062/cpre.20200123.

[89] F. Yang, N. Shen, A. Hu, A study of green technology innovation effects of low carbon pilot policies - evidence based on micro quasi-natural experiments, Soft Sci. 36 (12) (2022) 35–41, https://doi.org/10.13956/j.ss.1001-8409.2022.12.05.

[90] F.F. Pan, J.H. Xu, L. Xue, Voluntary environmental regulation: research progress and future prospects, China Population-Resources and Environment 30 (1) (2020) 74–82, https://doi.org/10.12062/cpre.20190822.

[91] S. Kumar, S. Shetty, Corporate participation in voluntary environmental programs in India: determinants and deterrence, Ecol. Econ. 147 (5) (2018) 1–10, https://doi.org/10.1016/j.ecolecon.2017.12.029.

[92] D.G. Rassier, D. Earnhart, Effects of environmental regulation on actual and expected profitability, Ecol. Econ. 112 (4) (2015) 129–140, https://doi.org/10.1016/j.ecolecon.2015.02.011.

[93] R. Li, R. Ramanathan, Exploring the relationships between different types of environmental regulations and environmental performance: evidence from China, J. Clean. Prod. 196 (2018) 1329–1340, https://doi.org/10.1016/j.jclepro.2018.06.132.

[94] X.D. Xu, S.X. Zeng, H.L. Zou, J.J. Shi, The impact of corporate environmental violation on shareholders' wealth: a perspective taken from media coverage, Bus. Strat. Environ. 25 (2) (2016) 73–91, https://doi.org/10.1002/bse.1858.

[95] Z.L. Wei, H. Shen, K.Z. Zhou, J.J. Li, How does environmental corporate social responsibility matter in a dysfunctional institutional environment? Evidence from China, J. Bus. Ethics 140 (1) (2017) 209–223, https://doi.org/10.1007/s10551-015-2704-3.

[96] J.Z. Xu, J. Guan, Y. Lin, Institutional pressure, executive environmental awareness and corporate green innovation practices - based on new institutionalism theory and higher order theory perspectives, Manag. Rev. 29 (9) (2017) 72–83, https://doi.org/10.14120/j.cnki.cn11-5057/f.2017.09.007.

[97] D. Gadenne, J. Kennedy, C. McKeiver, An empirical study of environmental awareness and practices in SMEs, J. Bus. Ethics 84 (1) (2008) 5–63, https://doi.org/10.2307/40294644.

[98] B. Zhang, Z.H. Wang, K.H. Lai, Mediating effect of managers' environmental concern: bridge between external pressures and firms' practices of energy conservation in China, J. Environ. Psychol. 43 (9) (2015) 203–215, https://doi.org/10.1016/j.jenvp.2015.07.002.

[99] S. Sharma, A.L. Pablo, H. Vredenburg, Corporate environmental responsiveness strategies the importance of issue interpretation and organizational context, Journal of Applied Behavioral Science A Publication of the Ntl Institute 35 (1) (1999) 87–108, https://doi.org/10.1177/0021886399351008.

[100] S. Kaplan, Research in cognition and strategy: reflections on two decades of progress and a look to the future, J. Manag. Stud. 48 (3) (2011) 665–695, https://doi.org/10.1111/j.1467-6486.2010.00983.x.

[101] D.F. Yang, J.H. Yang, R.P. Lou, Q. Yao, The influence of stakeholders, management perceptions on the choice of corporate environmental protection strategies–An empirical study based on listed enterprises in China, Manag. Rev. 24 (3) (2012) 140–149, https://doi.org/10.14120/j.cnki.cn11-5057/f.2012.03.006.

[102] Y.N. Li, F. Ye, Top management support, environmental innovation practices and firm performance - the moderating role of resource commitment, Manag. Rev. 25 (1) (2013) 120–127+166, https://doi.org/10.14120/j.cnki.cn11-5057/f.2013.01.017.

[103] S.C. He, X. Huang, Q. Chen, Can managers' environmental perceptions enhance firm performance - the mediating role of forward-looking environmental strategies and the moderating role of business environment uncertainty, Nankai Business Review 19 (6) (2016) 49–57, https://doi.org/10.3969/j.issn.1008-3448.2016.06.006.

[104] Z.W. Chen, D. Chen, How executive environmental awareness styles enhance firm performance in the context of environmental uncertainty of the old and new dynamics - the mediating role of green innovation, Science of Science and Management of S.& T. 40 (10) (2019) 113–128.

[105] X.R. Peng, Y. Liu, Behind eco-innovation: managerial environmental awareness and external resource acquisition, J. Clean. Prod. 139 (15) (2016) 347–360, https://doi.org/10.1016/j.jclepro.2016.08.051.

[106] J. Hojnik, M. Ruzzier, The driving forces of process eco-innovation and its impact on performance: insights from Slovenia, J. Clean. Prod. 133 (10) (2016) 812–825, https://doi.org/10.1016/j.jclepro.2016.06.002.

[107] J. Sarkis, P. Gonzalez-Torre, B. Adenso-Diaz, Stakeholder pressure and the adoption of environmental practices: the mediating effect of training, J. Oper. Manag. 28 (2) (2010) 163–176, https://doi.org/10.1016/j.jom.2009.10.001.

[108] H.J. Cao, Z.W. Chen, The driving effect of internal and external environment on firms' green innovation strategy - the moderating role of executives' environmental awareness, Nankai Business Review 20 (6) (2017) 95–103.

[109] R. Gholami, A.B. Sulaiman, T. Ramayah, A. Molla, Senior managers' perception on green information systems (IS) adoption and environmental performance. Results from a field survey, Inf. Manag. 50 (7) (2013) 431–438, https://doi.org/10.1016/j.im.2013.01.004.

[110] H. Xu, Q. Nie, X.H. Zhou, A study on the impact of IPO overcapitalization on corporate investment in environmental protection–based on the perspective of GEM listed enterprises, Financial Regulation Research 2 (2022) 81–97, https://doi.org/10.13490/j.cnki.frr.2022.02.005.

[111] A.E. Pan, Q.S. Guo, Government regulation and corporate environmental information disclosure - the moderating role of environmental awareness based on executives, Soft Sci. 32 (10) (2018) 84–87, https://doi.org/10.13956/j.ss.1001-8409.2018.10.19.

[112] Q. Lu, Q.H. Wu, Y.Z. Zhou, H.J. Zhou, A study on the evaluation of green transformation and upgrading of industry in Guangdong Province, China Population, Resour. Environ. 7 (2013) 34–41, https://doi.org/10.3969/j.issn.1002-2104.2013.07.006.

[113] A.M. Zhang, X.B. Li, J. Jie, W.H. Wu, X.N. Yang, Environmental regulation, agency costs and firm performance - empirical evidence from listed enterprises in the chemical industry, Accounting Research 8 (2021) 83–93, https://doi.org/10.3969/j.issn.1003-2886.2021.08.006.

[114] R.Y. Ying, L. Zhou, Foreign direct investment, industrial pollution and environmental regulation- an econometric analysis based on Chinese data, Finance & Trade Economics 1 (2006) 76–81, https://doi.org/10.19795/j.cnki.cn11-1166/f.2006.01.014.

[115] M. Yang, E.Z. Wang, C.S. Ye, Environmental management system certification and the export of Chinese manufacturing enterprises, China Industrial Economics 6 (2022) 155–173, https://doi.org/10.19581/j.cnki.ciejournal.2022.06.013.

[116] J.Z. Wu, Y.S. Bi, Executive team attention allocation and corporate internationalization strategy choice– A case study of Huawei, J. Manag. 9 (2013) 1268–1274, https://doi.org/10.3969/j.issn.1672-884x.2013.09.003.

[117] J. Hausman, H.Z. Griliches, Econometric models for count data with an application to the patents-R&D relationship, Econometrica 52 (4) (1984) 909–938, https://doi.org/10.2307/1911191.

[118] Z.L. Wen, J.T. Hou, L. Zhang, Comparison and application of moderating and mediating effects, J. Psychol. 2 (2) (2005) 268–274. CNKI:SUN:XLXB.0.2005-02-00F.

[119] G.X. Zhang, Y.C. Feng, A.L. Wang, A study on the heterogeneous role of different types of environmental regulations on technological innovation in industrial firms, Manag. Rev. 33 (1) (2021) 92–102, https://doi.org/10.14120/j.cnki.cn11-5057/f.2021.01.007.

[120] X.H. Zhu, X.G. Zuo, H.L. Li, The dual effects of heterogeneous environmental regulation on the technological innovation of Chinese steel enterprises -Based on a high-dimensional fixed effects model, Ecol. Econ. 188 (10) (2021), 107113, https://doi.org/10.1016/j.ecolecon.2021.107113.

[121] H. Wang, H. Sun, H.Y. Xiao, L. Xin, The relationship between environmental policy uncertainty, two-way FDI and low-carbon total factor productivity, China Population, Resour. Environ. 30 (11) (2020) 75–86, https://doi.org/10.12062/cpre.20200601.

[122] X.C. Tan, Q.Q. Zhang, E. Zeng, X.C. Xing, The impact of environmental regulations on the level of investment in renewable energy enterprises, China Population, Resour. Environ. 32 (7) (2022) 127–136, https://doi.org/10.12062/cpre20220601.

[123] Y. Wang, L.H. Yu, A study on the impact of environmental regulatory instruments on firms' preference for green technology innovation, Manag. Rev. 35 (2) (2023) 156–170, https://doi.org/10.14120/j.cnki.cn11-5057/f.2023.02.005.

[124] J. Hu, T.J. Tang, X.Z. Song, A study on the driving mechanism of corporate environmental governance: a perspective on the change of environmental officials, Nankai Business Review 22 (2) (2019), https://doi.org/10.3969/j.issn.1008-3448.2019.02.009.

[125] H. Wang, H. Sun, H.Y. Xiao, L. Xin, Cautious" or "risky"? –Environmental policy uncertainty and green innovation in pollution-intensive enterprises, Ind. Econ. Res. 2 (2021) 30–41+127, https://doi.org/10.13269/j.cnki.ier.2021.02.003.

[126] X.L. Wang, B.J. Chu, H. Ding, A.S.F. Chiu, Impacts of heterogeneous environmental regulation on green transformation of China's iron and steel industry: evidence from dynamic panel threshold regression, J. Clean. Prod. 382 (2023), 135214, https://doi.org/10.1016/j.jclepro.2022.135214.

[127] X. Li, K. Du, X. Ouyang, L. Liu, Does more stringent environmental regulation induce firms' innovation? Evidence from the 11th Five-year plan in China, Energy Econ. 112 (8) (2022), 106110, https://doi.org/10.1016/j.eneco.2022.106110.

[128] P. Zhang, P.P. Zhang, G.Q. Cai, A comparative study on the impact of different types of environmental regulations on enterprises' technological innovation, China Population, Resour. Environ. 26 (4) (2016) 8–13, https://doi.org/10.3969/j.issn.1002-2104.2016.04.002.

[129] Z.Y. Jiang, Z.J. Wang, X. Lan, How environmental regulations affect corporate innovation? The coupling mechanism of mandatory rules and voluntary management, Technol. Soc. 65 (5) (2021) 101575, https://doi.org/10.1016/j.techsoc.2021.101575.

Yongjun Tang graduated from Nanjing University and obtained a PhD. He is an associate professor in Business School of Hohai University. His research interests focus on information disclosure, environmental accounting, intelligent accounting, value management and distribution of enterprises. His studies have been published in accounting research (in Chinese), Emerging Markets Finance & Trade, Environmental Science and Pollution Research and other journals. Email: yjtang@hhu.edu.cn; atang508@126.com.

Yuqiu Qi is a postgraduate student of Hohai University. Her interests focus on environmental accounting and enterprise value. Email: qyq19990802@163.com.

Fen Zhou is an associate professor in School of Accounting of Nanjing University of Finance & Economics. She is the correspondent of this study. Her interests focus on technical economy and management, banking finance, corporate finance. Email: fenzhounufe@126.com.

Lei Hua is a student of Tianjin university of technology. Her interests focus on corporate management and environmental management. Email: hualei02@stud.edu.cn.