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Climate Policy, Environmental Attention, and Industrial Chain Green Resilience: Evidence from Machine Learning

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***Abstract*— *Addressing environmental issues and improving resilient production have become urgent priorities, making green resilience a crucial focus across all areas of society. However, the effects of climate policy on industrial chain green resilience (ICGR) and the pathways for enhancing ICGR are not well known. To this end, this study utilizes the machine learning algorithms to investigate the impact of the China's low-carbon city pilot (LCCP) on ICGR, with a particular focus on the potential indirect effects mediated by environmental attention. The results reveal that: The LCCP has promoted ICGR in pilot cities, a conclusion that has been substantiated as highly robust through double dual machine learning and generalized random forest approaches. Additionally, the LCCP boosts ICGR by reinforcing government environmental attention and public environmental concern. Specifically, government environmental attention shows a "ceiling" effect, while the relationship between public environmental concern and the treatment effect follows an inverted U-shaped pattern. It is hoped that the insights gained from this study will contribute to strengthening urban development resilience and facilitating sustainable progress.*

***Keywords*— *Low-carbon city pilot; Climate policy; Industrial chain green resilience; Double dual machine learning; Generalized random forest; Environmental attention.*

I. Introduction

Humanity consistently confronts crises, including global natural disasters, public health emergencies, and geopolitical conflicts. When these crises intersect with additional factors such as economic downturns or environmental challenges, they are likely to exert profound influences, triggering cascading effects that undermine stability. Therefore, resilience must be considered when formulating strategies to achieve environmental sustainability goals[1]. China's rapid economic development has led to substantial environmental pollution issues. To address these challenges, China has implemented a series of environmental regulatory measures, including the Low-carbon city pilot (LCCP) program. According to the Porter hypothesis, within the global value chain division of labor, the interplay between domestic environmental regulations and foreign green barriers, coupled with weak indigenous innovation capabilities, may result in a "low-end lock-in" of green technology[2]. This situation may subsequently lead to a protracted process of industrial transformation and upgrading. Given the inherent risks associated with technological innovation and the complexity of industrial chain networks, it has become imperative to balance green and secure development under internal and external pressures. The focus should shift towards strengthening the capacity of industrial chains to withstand and recover from risks, which in turn enhances economic resilience.

Growing concerns over the deteriorating ecological environment have fostered a green mindset among consumers, governments, and businesses[3], prompting the integration of environmental sustainability measures into supply chain management practices[4]. Resilience is understood as a multidimensional concept that is managed in diverse ways to achieve different objectives. Drawing on resilience-related definitions pertinent to diverse research aims[5], we define industrial chain green resilience (ICGR) as the capacity of the industrial chain network to adapt to environmental regulatory requirements through technological innovation and the adoption of green production methods in response to external shocks, thereby enabling the restoration of balanced industrial development and facilitating a gradual transition towards a sustainable production model.

In this context, a pertinent question arises: Will cities across diverse industrial chains in pilot regions enhance their green resilience to cope with the foreseeable intensification of environmental regulatory pressures and other potential shocks? If we consider environmental regulation policies as one of the shocks impacting industrial chain's survival and development, then enhancing green resilience becomes an area of significant research value in achieving a balance between business sustainability and environmental protection.

The marginal contributions of this paper include: First, in contrast to previous studies that primarily examined the impact of climate policies on carbon emission reduction, this paper underscores the resilience-building potential and green development achieved through urban industrial chains' capacity to adapt to environmental policy changes and unforeseen events, referred to as ICGR. This perspective not only enhances the scholarly discourse surrounding the LCCP but also complements existing studies on economic resilience. Second, this paper employs double dual machine learning (DDML) and generalized random forest (GRF) for causal identification. In contrast to traditional fixed effects models, DDML obviates the need for a predetermined functional form. Machine learning algorithms demonstrate exceptional performance in high-dimensional, non-parametric prediction tasks, facilitating more precise estimation of treatment effects and thereby bolstering the credibility of the study's conclusions. Third, this paper utilizes causal mediation analysis with DDML[6], focusing on environmental attention perspective. We examine the mediating roles of government environmental attention and public environmental concern. It is hoped that this study will offer valuable insights for improving the implementation of the LCCP and enhancing the green resilience of industrial chain networks from the perspective of environmental attention.

II. METHODOLOGY

A. Method

In this study, we employ the DDML model[7] and GRF model[8] to assess the policy impact of the LCCP on ICGR. In high-dimensional and non-parametric prediction tasks, DDML exhibits particular effectiveness, facilitating enhanced accuracy in the estimation of treatment effects. Unlike conventional random forests, GRF is custom-built for causal inference tasks, equipping it to quantify causal effects despite the existence of confounding variables.

B. Data

Dependent variable (ICGR): Building on existing literature and available data[9,10], we construct the ICGR index system to capture the supply chain's evolutionary stage. This system is operationalized across three theoretically grounded dimensions: diversity, adaptability, and environmental sustainability, with component weights determined using the entropy method.

Policy variable (LCCP): $LCCP_{it}$ is defined as whether city *i* was selected as a pilot city in year *t*.

Mediating variable: This paper aims to analyze the impact mechanism of the LCCP on ICGR from both internal and external perspectives of environmental attention. As the local government is primarily responsible for policy implementation and enforcement, we use governmental environmental attention (GEA) as an internal proxy variable. Since individuals are typically the ultimate target audience of policies, we utilize Public environmental concern (PEC) as an external proxy. GEA is measured by quantifying the frequency of environment-related terms in the government's annual work reports[11]. The PEC data is collected from the Baidu Index[12] .

Control variables: Following previous research[10,11], the control variables are detailed as follows: Population density (natural logarithm of population density), Economic level (natural logarithm of per capita GDP), Education level (education expenditure as a share of GDP), Trade openness level (total import and export volume as a share of GDP).

III. RESULTS

A. Policy effect

As shown in Table 1, the DDML and GRF results corroborate that the regression coefficient of LCCP on ICGR is consistently positive and significant at the 1% level. This implies that LCCP has a beneficial effect on ICGR in pilot cities. Low-carbon pilot cities usually implement policies and measures to reduce carbon emissions. The measures may involve promoting renewable energy and emission-reduction technologies to encourage technological innovation and foster a green transformation within the industrial chain[13]. Additionally, pilot cities may optimize resource allocation and energy efficiency[14], urging enterprises to reduce resource waste and pollution during production. This optimization lowers operational costs and boosts the efficiency and sustainability of the industrial chain. Furthermore, pilot cities use green finance and investment to support low-carbon projects and technologies.

TABLE 1. Results of policy effect

Variables	DDML		GRF	
	(1)	(2)	(3)	(4)
LCCP	0.0146***	0.0170***	0.0196***	0.0197***
	(0.0015)	(0.0022)	(0.0043)	(0.0044)
controls	YES	YES	YES	YES
training set			60%	70%
Trees			20000	4000
Obs	4480	4480	4480	4480

Note: The robust standard errors statistics in parentheses; * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$; the following tables are the same.

B. Causal mediation analysis

We utilize post-lasso regression[6] to test the indirect effect. Table 2 presents the average treatment effect (ATE) of implementing the LCCP on ICGR, along with the average indirect effects mediated by GEA and PEC. We find that the ATE estimators for both GEA and PEC are statistically significant, with positive coefficients, as shown in column (1). The results further confirms the positive impact of the LCCP on ICGR. The positive indirect effects of the mediators, as shown in columns (4) and (5), indicate that the LCCP enhances ICGR by increasing GEA and PEC.

TABLE 2. Results of Causal mediation analysis

	ATE	Direct effect		Indirect effect	
	(1)	(2)	(3)	(4)	(5)
GAP	0.0231***	0.0222***	0.0185***	0.0046***	0.0009***
	(0.0018)	(0.0018)	(0.0016)	(0.0009)	(0.0002)
PEC	0.0073***	0.0026**	0.0028***	0.0045***	0.0047***
	(0.0014)	(0.0012)	(0.0010)	(0.0014)	(0.0009)

The LCCP suffers from weak constraints, making policy goals hard to quantify, and the disparity between regional policies and their implementation presents a major challenge. Government focus on environmental issues has redirected public resources to the environmental protection field[12], compelling businesses to adjust their operations and strategies, acting as a "weather vane". Regarding PEC, it encourages investment in sustainable development and motivates companies to incorporate more sustainability factors into their business decisions[15]. Growing public interest in corporate environmental responsibility necessitates that companies understand and disclose their supply chains' environmental impacts, including raw material sources, production emissions, and product life cycle management. An example of this driving force is that consumers are willing to pay more for green products that offer additional ecological benefits. Additionally, companies might collaborate with others in the supply chain to develop and implement sustainable solutions, thereby accelerating environmental innovation across the industrial chain[16]. This dual approach of internal and external monitoring not only ensures the green transformation of the industrial chain but also motivates enterprises within the chain to move beyond their "wait-and-see" stance in response to climate policy uncertainty. They drive enterprises to adopt cleaner and more sustainable production methods, ultimately enhancing regional ICGR.

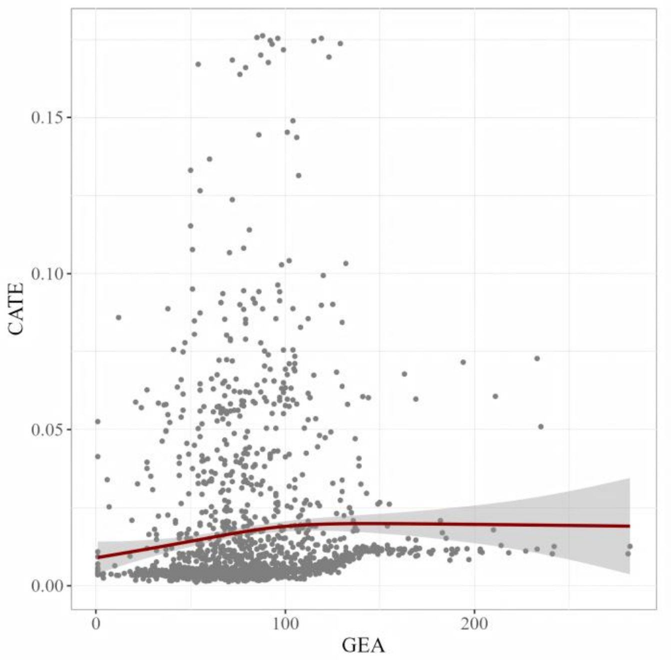

Fig. 1. The effect of the LCCP changes with the change of GEA.

After identifying the indirect effects of GEA and PEC, we further examined their heterogeneous effects using the GRF algorithm. Fig. 1 illustrates the relationship between the conditional average treatment effects (CATE) of the LCCP and GEA. The CATE initially rises with an increase in GEA, but after GEA surpasses a certain threshold, the CATE plateaus, indicating a "ceiling" effect of GEA. Fig. 2 depicts the treatment effect of PEC within the LCCP policy framework. The CATE exhibits an inverted U-shaped relationship with PEC, suggesting that a moderate level of PEC is more beneficial for enhancing ICGR. The potential reason is that while initial PEC positively impacts ICGR, continued attention may be hindered by complex economic, social, and technological factors, creating an inverted U-shaped relationship. Under public pressure and social responsibility, enterprises and industrial chains often implement proactive environmental measures to boost green resilience. However, as these measures intensify, enterprises may encounter increased costs and resource limitations. In enterprises facing significant consumer pressure, an increase in PEC results in decreased output[17]. To maintain profitability, these enterprises prioritize satisfying the most influential stakeholder groups[18]. Our findings reveal the disparities in the treatment effects of GEA and PEC, underscoring the importance of multi-stakeholder engagement for effective environmental supervision and resilient governance.

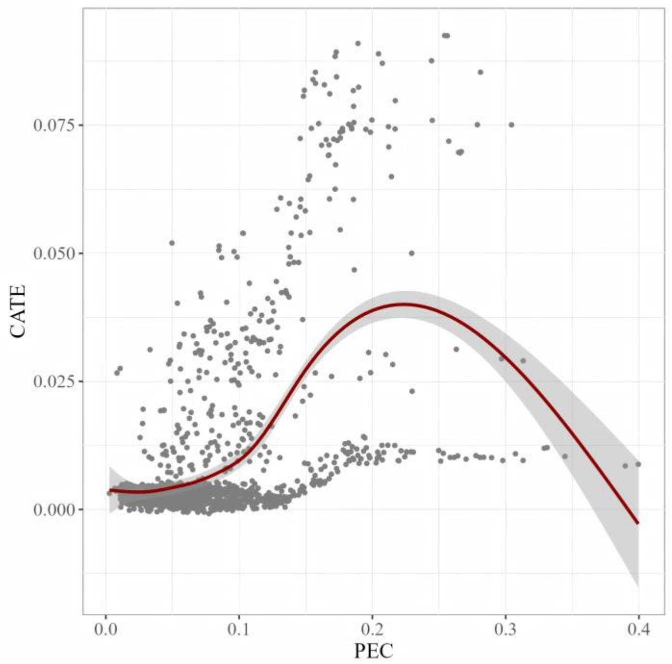

Fig. 2. The effect of the LCCP changes with the change of PEC.

IV. CONCLUSIONS

The main research conclusions are as follows: (1) LCCP has a significant positive impact on the ICGR of pilot cities. (2) LCCP improves urban ICGR indirectly by influencing GEA and PEC. The promoting effect of GEA is limited; once it surpasses a certain threshold, CATE ceases to increase with further increases in GEA. An inverted U-shaped relationship exists between PEC and CATEs, where an excessively high PEC diminishes the effect of LCCP.

V. POLICY IMPLICATIONS

The proposed policy recommendations are as follows: (1) Policymakers should incrementally broaden the reach of low-carbon pilot cities, fine-tune project criteria, and concurrently implement a dynamic evaluation system to assess the sustainability of policy impacts. (2) Local governments should create effective communication channels, enhance the transparency of environmental information disclosure by enterprises, and encourage diverse social governance to address the limitations of governmental oversight.

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