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A Study on the Carbon Emission Reduction Effects of Urban Green Innovation—From the Perspective of the Moderating Role of Environmental Information Disclosure

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Abstract. As one of the informal environmental regulations, the environmental information disclosure system plays a significant role in energy conservation and emissions reduction due to its flexible and efficient nature. Based on urban panel data from 2012 to 2022, this study conducts an empirical analysis of the carbon emission reduction effects of urban green innovation. The analysis focuses on 120 cities nationwide included in the Pollution Source Oversight Information Disclosure Index, as reported in the annual report jointly published by the Institute of Public and Environmental Affairs (IPE) and the Natural Resources Defense Council (NRDC).Furthermore, this study examines the moderating role of environmental information disclosure in the carbon emission reduction effects of urban green innovation, providing valuable insights for further exploring the effectiveness of promoting and implementing the environmental information disclosure system.

Keywords: urban green innovation, carbon emission reduction, environmental information disclosure, level of green innovation, moderating effect

1. Introduction

In response to climate issues, China has actively implemented various measures to promote energy conservation and emission reduction, as well as to facilitate the transition to a low-carbon economy [1]. The "Dual Carbon" goals, established as key targets for energy conservation and emissions reduction in China, are driving various stakeholders to actively engage in energy-saving, emissions-reduction, and carbon-reduction initiatives [2]. Consequently, on China's path toward green and low-carbon development, effectively reducing urban carbon emissions has become an urgent issue requiring resolution.

Green technological innovation plays a vital role in promoting green economic development [3]. Urban green innovation, as an organic integration of innovation effectiveness and environmental protection at the urban level, is a key research focus within the carbon reduction agenda. In-depth exploration of the carbon reduction effects of urban green innovation is crucial for building environmentally friendly green cities and achieving energy conservation, pollution reduction, and carbon reduction.

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The development of green technological innovation is influenced by environmental regulatory factors [4]. The environmental information disclosure system, as an informal environmental regulatory tool, has achieved greater efficiency and flexibility compared to traditional regulatory measures such as administrative controls [5]. Therefore, studying the significant role of environmental information disclosure in carbon emission reduction effects and further quantifying its capacity for "pollution and carbon reduction" holds important implications for both theory and practice.

2. Theoretical framework and hypotheses

2.1. Mechanism analysis of the carbon emission reduction effects of urban green technological innovation

Urban green technological innovation reduces reliance on fossil fuels through the development of renewable energy, improves soil health by researching sustainable agricultural methods and practices, and thereby achieves the goals of enhancing energy efficiency, optimizing the energy mix, and upgrading carbon capture and utilization technologies. It also minimizes the environmental impact of the transportation sector, allowing urban green technological innovation to maximize the utilization of renewable energy.In terms of specific mechanisms, urban green technology innovation influences carbon emission intensity through industrial structure upgrading, the regulatory role of human capital, and improved energy efficiency, thereby achieving carbon emission reductions.

2.2. Analysis of the impact mechanism of environmental information disclosure on urban green innovation

There is a synergistic relationship between environmental information disclosure and urban green innovation. On the one hand, environmental information disclosure provides the informational foundation and social impetus for urban green innovation, and it can facilitate urban green innovation through intermediaries such as promoting the development of green finance and improving energy efficiency [6]; on the other hand, the development of urban green innovation also helps enhance the quality and effectiveness of environmental information disclosure.For example, the application of green innovation technologies can reduce pollutant emissions and improve environmental quality, thereby enhancing the credibility and persuasiveness of environmental information disclosure.

3. Research design

3.1. Specification of the econometric model

3.1.1. Dual fixed-effects model

To examine the impact of urban green innovation on carbon emissions, this study constructs the following two-way fixed-effects model:

$$CI_{i,t} = \beta_0 + \beta_1 LnGP_{i,t} + \lambda_i \sum_{k=1}^{n} Control_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t} \quad (1)$$

In Equation (1), $Etr_{i,t}$ is the dependent variable, i.e., carbon emissions; $LnGP_{i,t}$ is the main independent variable, i.e., the level of green innovation in city c; $Control_{i,t}$ represents a set of

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control variables. i denotes the city, t denotes the year, μ_i is the individual fixed effect, $\tau_{(t)}$ is the time fixed effect, and $\varepsilon_{i,t}$ is the random error term.

3.1.2. Dual fixed-effects model

By calculating the interaction term between urban green innovation and environmental information disclosure and introducing it into the model as an explanatory variable, this study examines how the impact of urban green innovation on carbon emissions varies across different levels of environmental information disclosure.

$$CI_{i,t} = \beta_0 + \beta_1 LnGP_{i,t} + \beta_2 PITI_{i,t} + \beta_3 LnGP \times PITI + \lambda_i \sum_{k=1}^{n} Control_{i,t} + \mu_i + \tau_t + \varepsilon_{i,t} \quad (2)$$

$PITI_{i,t}$ To measure the degree of environmental information disclosure, This article focus primarily on the moderating effect of the regression coefficient for the interaction *term* Nqp × Iprp. Specific variable definitions and measurement methods will be introduced below. Definitions of other variables in the model remain consistent with those in the preceding sections.

3.2. Dependent variables

In this paper, carbon emission reduction effects are measured using carbon intensity (CI_{it}). The formula for carbon intensity is as follows:

$$CI_{it} = ln\left(\frac{CE_{it}}{GDP_{it}}\right) \quad (3)$$

where GDP_{it} represents regional gross domestic product, and CE_{it} represents regional carbon emissions.

Measure the relationship between provincial carbon emissions and nighttime light intensity values, and construct a model as follows:

$$CE_{it}^{P} = \gamma \times NL_{it}^{P} + \varphi_i + \omega_t + \varepsilon_{it} \quad (4)$$

Secondly, Using provincial carbon emissions and provincial and municipal-level nighttime light intensity values, a two-way fixed-effects model (TWFE) is applied to estimate the coefficient γ and provincial carbon emissions. A top-down model is then constructed as follows to estimate municipal-level carbon emissions:

$$CE_c = CE_p \times (CE_c\prime / CE_p\prime) = CE_p \times \left[\frac{(\gamma\prime \times NL_c + \varphi_i\prime + \omega_t\prime)}{(\gamma\prime \times NL_p + \varphi_i\prime + \omega_t\prime)}\right] \quad (5)$$

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4. Analysis of empirical results

4.1. Baseline regression analysis

Based on a pre-specified baseline regression model, This article conducted an empirical analysis using the collected sample data to assess the role of urban green innovation in carbon emissions reduction. The baseline regression model was evaluated using the Hausman test, and the results were significant at the 1% level, thereby rejecting the applicability of the random-effects model. Accordingly, This article selected the fixed-effects model as the primary tool for subsequent analysis to ensure that the analysis could capture structural changes in the data.The regression results show that, under the assumption of double fixed effects, the regression coefficient of the core explanatory variableLnGP is significantly negative. This finding is further reinforced by the fact that, even after incorporating multiple control variables, the regression coefficient remains significant at the 1% level, and the magnitude of the coefficient's change is limited.

4.2. Robustness tests

Based on research experience and econometric theory, the baseline regression results may exhibit some bias in reflecting the study's conclusions. To ensure the robustness of the conclusions, this paper conducts a comprehensive and detailed robustness analysis of the regression results. The following five methods are employed for the robustness analysis:

a. Re-estimating the model by excluding the four municipalities and conducting subsample regressions;

b. Truncating all variables at 5% to avoid the influence of outliers;

c. Replacing the dependent variable;

d. Controlling for the combined effects of time and city;

e. Employing the instrumental variables method to mitigate endogeneity issues.

4.2.1. Replacing the dependent variable

Out of a thorough consideration of practical utility, this study selected the number of authorized green invention patents as the dependent variable. However, to further examine the robustness of the conclusions, This article first substitute the number of authorized green invention patents with the number of green invention patent applications, and further decompose this into the number of green invention patent applications (GIP) and the number of green utility model patent applications (GUP), using these two variables to replace the original dependent variable.Regression analysis was conducted on the filtered sample, and the results are shown in columns (3) and (4) of Table 4-2: after substituting the dependent variables, LnGIP and LnGUP are significant at the 1% and 10% levels, respectively, further validating the robustness of the results.

4.2.2. Instrumental variables method

Regarding the discussion of endogeneity, carbon emissions are likely to drive improvements in urban green innovation levels by attracting government attention and prompting the introduction of relevant policies, which may conceal potential reverse causality issues. To address this issue, first, current-period carbon intensity cannot influence the previous period's urban green innovation levels, urban economic development levels, or urbanization rates. To eliminate endogeneity issues that may arise from the explanatory variables,this study employs the first-order lagged term of urban green

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innovation as an instrumental variable to reduce cointegration among variables. Furthermore, two-stage least squares (2SLS) is utilized as the analytical tool. On this basis, all explanatory variables are subjected to a one-period lag treatment to ensure rigorous statistical testing.The results are shown in Table 4-3: In the first stage, a significant positive correlation exists between the instrumental variable and urban green innovation, validating the appropriateness and effectiveness of the selected instrumental variable; in the second stage, the regression results for both treatment methods remain significantly positive at the 1% level, a finding that clearly demonstrates the robustness of the carbon emission reduction effect of urban green innovation.

4.3. Heterogeneity analysis

The samples used in this study are drawn from various prefecture-level cities. Given differences in geographic location and resource endowments, the impacts of urban green innovation may exhibit a certain degree of heterogeneity. To address this issue, this study conducts a classified regression analysis on the entire sample based on the dual heterogeneity of geographic location and resource endowments, aiming to thoroughly investigate the differentiated effects of urban green innovation on carbon emission intensity.

4.3.1. Differences in geographic location

Different regions have varying levels of development, which typically leads to heterogeneous results. The sample was divided into three major regions—Eastern, Central, and Western—based on geographic location, and regression analyses were conducted separately for each. Among them, the regression coefficients for the Eastern, Central, and Western regions all showed a negative correlation, consistent with empirical observations.However, among the three regions, only the eastern region showed a statistically significant negative correlation, and the carbon emission reduction effect of urban green innovation in the eastern region was far stronger than that in the central and western regions. This phenomenon may be attributed to the eastern region's higher overall level of development and modernization, as well as a greater concentration of innovation actors. The high priority and implementation of urban green innovation, coupled with well-developed infrastructure, are more conducive to translating the outcomes of urban green innovation into a significant reduction in carbon emission intensity.Furthermore, in China's overall energy structure, the central and western regions bear a greater share of energy production, and the distribution of large-scale thermal power plants in these two regions far exceeds that in the eastern region. Consequently, the extent to which urban green innovation reduces carbon emission intensity is significantly affected. Although geographical differences exist, the generally negative effect of urban green innovation indicates that it effectively enhances environmental protection and climate mitigation, holding significant importance and value for the achievement of the "dual carbon" goals.

4.3.2. Differences in economic foundations

Regions with strong economic foundations, backed by well-developed infrastructure systems, not only accelerate the introduction and implementation of new technologies and business models but also facilitate the free flow and efficient integration of urban green innovation outcomes within the region, providing robust material support for urban green innovation to achieve carbon emission reduction effects. Conversely, regions with relatively weak economic foundations suffer from lagging infrastructure development, which acts as a bottleneck constraining the improvement of

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urban green innovation levels and weakens these regions' ability to reduce carbon emission intensity.This paper divides the study area into two major groups based on whether they are located within the Yangtze River Economic Belt. It can be seen that the urban green innovation coefficients for regions within the Yangtze River Economic Belt all exhibit a statistically significant negative effect at the 1% significance level, and the coefficient for suppressing carbon emission intensity is nearly double that of regions outside the Yangtze River Economic Belt. This clearly demonstrates that in regions with a strong economic foundation, the carbon emission reduction effects of urban green innovation can be better realized, which is consistent with the performance observed in the eastern region in the previous analysis.

4.3.3. Differences in resource endowments

Resource-based cities are those whose dominant industries revolve around the extraction and processing of local natural resources such as minerals and forests. They serve as vital strategic bases for energy and resource security in China and are crucial for the sustained and healthy development of the national economy. The realization of the carbon emission reduction effects of urban green innovation is closely linked to a city's basic resource conditions and requires the enabling role of urban resources.

4.4. Moderation effect analysis

By calculating the interaction term between urban green innovation and environmental information disclosure and introducing it into the model as an explanatory variable, this study examines how the impact of urban green innovation on carbon emission intensity varies across different levels of environmental information disclosure.

$$CI_{i,t} = \beta_0 + \beta_1 LnGP_{i,t} + \beta_2 PITI_{i,t} + \beta_3 LnGP \times PITI + \lambda_i \sum_{k=1}^{n} Control_{i,t} \quad (6)$$
$$+\mu_i + \tau_t + \varepsilon_{i,t}$$

$PITI_{i,t}$ To measure the degree of environmental information disclosure, This article focus on the moderation effect regression analysis of the regression coefficient for the interaction term ` $LnGP \times PITI$ `.

5. Conclusions

mpact of urban green innovation on carbon emission intensity. The conclusions are as follows: First, an increase in the level of urban green innovation can significantly curb the rise in carbon emission intensity; Second, an increase in the level of environmental information disclosure can significantly curb the rise in carbon emission intensity; Third, environmental information disclosure has a moderating effect on the carbon emission reduction effect of urban green innovation, enhancing the role of urban green innovation in reducing carbon emissions;Fourth, the carbon emission reduction effect of urban green innovation is more pronounced in eastern cities, cities along the Yangtze River Economic Belt, and non-resource-based cities.

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