ISSN 2522-3488 Vol. 7, Issue 7: 21-33, DOI: 10.25236/IJNDES.2023.070704

A Study on the Impact of Network Infrastructure Development on Carbon Emissions in China's Border Regions

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Abstract: *In the context of the digital economy, selecting a viable approach to achieve the strategic objective of reducing carbon emissions is pivotal for facilitating the high-quality development of China's border region economy. This study conducts an empirical analysis using panel data encompassing 75 cities within the border region spanning from 2006 to 2018. Leveraging the quasi-natural experiments presented by the pilot policy of the "Broadband China" strategy, and employing the multi-period double-difference methodology, this paper unveils compelling insights. The findings reveal that the pilot policy of the "Broadband China" strategy significantly diminishes the carbon emission levels within the border cities. This observation remains consistent even after eliminating potential non-random selection factors and external policy influences. When comparing the results with the eastern and southwestern counterparts, it becomes evident that the impact of network infrastructure development on carbon emissions reduction is more pronounced in the central and western regions, as well as the northeastern and northern border areas. Mechanism analysis outcomes underscore that the construction of network infrastructure drives carbon emission reduction in border areas by catalyzing shifts in industrial structure and fostering advancements in green innovation within these urban centers. Against the backdrop of the digital economy, this study delves into pathways for realizing the strategic goal of curbing carbon emissions in border regions, thus furnishing valuable insights for these areas to seize emerging opportunities in the unfolding scientific and technological revolution and the transition toward a greener economy.*

Keywords: *Border areas, network infrastructure construction, carbon emission, "Broadband China" strategy, multi-period double-difference methods*

1. Introduction

The concept of high-quality development was initially introduced in the report of the 19th CPC National Congress, signifying a pivotal shift in China's economy from a phase of high-speed growth to one characterized by high-quality development. This report distinctly underscores the indispensable role of green development in achieving high-quality progress, calling for the establishment of a robust framework centered around green, low-carbon, and circular economic principles. As the Internet era unfolds, the surge of emerging technologies like big data, artificial intelligence, 5G technology, cloud computing, and blockchain has unleashed fresh perspectives for driving green economic growth. In 2013, the State Council responded by issuing the "Circular on the Strategy and Implementation Plan for Broadband China." This landmark document, aligned with the National Informatization Development Strategy 2006-2020 and the aspirations of the 12th Five-Year Plan, laid the foundation for the subsequent approval of the inaugural batch of "Broadband China" projects by the Ministry of Industry and Information Technology (MIIT) and the National Development and Reform Commission (NDRC) in 2014. The comprehensive strategy set forth a phased approach: acceleration up to 2013, promotion and popularization between 2014 and 2015, and optimization and upgrading spanning 2016 to 2020. The latter phase targeted improvements in service quality, application proficiency, and industrial support to global standards. This strategy has had far-reaching effects. It spurred the construction of network infrastructure, propelled the growth of regional Internet broadband and information network industries, and elevated informatization levels across diverse regions. Of significant note is the pivotal role border areas play in China's high-quality economic development. Yet, challenges persist due to constraints such as limited capital, technology, talent, and innovation capacity. As a result, these regions have largely experienced crude growth patterns, with coal consumption retaining a substantial share of

ISSN 2522-3488 Vol. 7, Issue 7: 21-33, DOI: 10.25236/IJNDES.2023.070704

industrial energy use, leading to considerable greenhouse gas emissions. The Northeast stands out as a key focus for national emission reduction efforts. Within this context, the question arises: Can network infrastructure construction contribute to energy conservation and emission reduction in border areas? What mechanisms drive this potential impact? Despite the wide incorporation of the Internet in corporate operations and daily life, empirical studies accurately assessing the influence of network infrastructure on carbon emissions are scarce, particularly within underdeveloped regions like border areas.

The existing research predominantly centers on the "Broadband China" strategy. Scholars such as Liu Yajun[1],Fan Hongzhong[2], Jie Zhang[3], and Yifei Zhang[4] have examined its impact on inter-city cooperation, innovation, industrial agglomeration, and enterprise transformation. In terms of urban and rural income dynamics, researchers like Chen Yang[5] and Hu Haoran[6] have explored the strategy's potential to narrow urban-rural income gaps through improved employment structures. However, minimal research delves into network infrastructure's role in influencing carbon emissions, especially within underdeveloped regions. While pollutants like CH_4[7], NO_2[7], SO_2[8], and PM2.5[9] have garnered attention, the focus on carbon emissions remains limited. Additionally, most studies adopt a national scope, neglecting examination of network infrastructure's implications for less-developed regions. Given the relatively underdeveloped state of network infrastructure in border areas, its potential to mitigate environmental pollution, enable energy conservation, and reduce emissions remains largely unexplored. Amidst ongoing new infrastructure development and high-quality progress, understanding whether the "Broadband China" strategy can stimulate low-carbon development in border areas holds immense theoretical and practical significance. This paper aims to address this crucial knowledge gap by investigating whether the "Broadband China" strategy can impact carbon emission reduction in border regions. The findings are expected to provide valuable policy insights, further driving network infrastructure construction and contributing to the realization of carbon peak and carbon neutrality goals.

2. Policy Background and Mechanism Analysis

2.1. Policy Background

For an extended period, China's network infrastructure construction has grappled with issues of regional imbalances, sluggish network speeds, and subpar network quality. These challenges have significantly impeded the advancement of China's industrial informatization. To propel the development and widespread adoption of broadband networks and fortify national informatization efforts, the State Council issued the "Circular of the State Council on the Issuance of the Strategy and Implementation Plan for Broadband China" in August 2013. This release was anchored in the National Informatization Development Strategy 2006-2020 and the objectives outlined in the 12th Five-Year Plan.

The "Broadband China" strategy maps out a three-phase developmental trajectory: The initial phase, culminating by the end of 2013, concentrates on comprehensive acceleration. This involves bolstering the construction of fiber-optic networks and 3G networks, elevating broadband network access rates, and enhancing users' internet experiences. The subsequent period spanning 2014-2015 is designated as the promotion and popularization phase. Here, the emphasis remains on advancing broadband network acceleration, expanding coverage and scope, and deepening the propagation of applications. From 2016 onwards, the strategy enters the optimization and upgrading phase. During this stage, the emphasis shifts towards enhancing broadband network optimization, technological evolution, and upgrading. The overarching aim is to elevate service quality, application proficiency, and industrial support capacity to a globally advanced level. Spanning these phases, the strategy outlines targets encompassing user scale, broadband penetration rate, access capacity, and the number of internet users. This strategic initiative categorizes broadband as a critical national infrastructure. The strategy's deployment is executed across three separate batches. In 2014, 2015, and 2016, a cumulative total of 119 cities were approved as demonstration cities for the "Broadband China" initiative. The progressive strategy underscores the critical role of broadband infrastructure in propelling China's digital advancement, addressing regional disparities, and fostering an inclusive digital society. It sets a forward-looking agenda for the integration of advanced technologies and robust network connectivity as key drivers of China's socio-economic growth.

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2.2 Theoretical Mechanisms and Research Hypotheses

2.2.1 The Direct Effect of Network Infrastructure Construction in Reducing Carbon Emissions in Border Areas

In the current landscape of informatization and digitalization, a novel avenue emerges for regional environmental governance. Network infrastructure construction, serving as the bedrock for optimizing the Internet ecosystem, possesses the potential to significantly enhance overall network information technology services within border regions. This, in turn, fosters the growth of Internet of Things, artificial intelligence, cloud computing, and other cutting-edge technologies, hastening their integration into enterprises. Such integration bolsters production efficiency, enabling high output levels from low-energy consumption scenarios, ultimately curbing energy use. Moreover, streamlined logistics and transportation are achievable through comprehensive network information systems, diminishing goods transshipment occurrences and reducing vehicle travel distances, thereby mitigating exhaust emissions. Within the production sphere, network information technology fuels the development of digital platforms in border regions. This platform-driven approach curbs information dissemination costs, bridging the information gap between consumers and suppliers. Consequently, suppliers can adroitly align inventory and production schedules with consumer demand, minimizing wastage and subsequently reducing carbon emissions in the production process. Direct carbon emission reduction can be realized through paperless offices, enhanced efficiency of regulatory agencies in monitoring pollutant emissions, broader avenues for public involvement in environmental pollution control, and heightened adoption of clean energy sources. In light of these insights, this paper advances the following hypothesis:

Hypothesis H1: The pilot policy of the "Broadband China" strategy can effectively curtail carbon emissions in border areas and foster low-carbon development.

2.2.2 Indirect Effect of Network Infrastructure Construction on Reducing Carbon Emissions in Border Areas

The "Broadband China" strategy, by engendering network infrastructure construction in border regions, possesses the capacity to catalyze the fusion of digital technology with conventional industries. This synergy engenders novel business and industrial models, thereby optimizing factor allocation and accelerating product innovation. Additionally, network infrastructure construction augments data's role as a production factor, diminishing reliance on fossil fuels in manufacturing. This, in turn, encourages the metamorphosis of high-energy-consumption, highly polluting, low-tech, and low-value-added traditional industries into greener counterparts characterized by lower energy consumption, reduced pollution, advanced technology, and heightened value addition. Consequently, the upgrade of industrial structure is promoted, offering respite from the tension between traditional industries' crude growth models and environmental preservation. Furthermore, network infrastructure construction diminishes information asymmetry through the propagation of information technologies like the Internet of Things, big data, and cloud computing. This, in turn, enhances optimal decision-making and resource allocation within enterprises, culminating in decreased carbon emissions during production. Accordingly, this paper posits the following hypothesis:

Hypothesis H2: The pilot policy of the "Broadband China" strategy can curtail carbon emission levels in border areas by optimizing the region's industrial structure.

Network infrastructure construction profoundly augments the level of green technological innovation within a region, thereby curbing carbon emissions through the energy-efficient attributes of digital technological advancement. First, as a pivotal component of urban infrastructure, the implementation of network infrastructure construction enhances living standards, fostering an environment conducive to green innovation. This is attributed to the improved quality of life and heightened human resources levels in urban areas. Second, network infrastructure dismantles temporal and spatial information dissemination limitations, ultimately reducing information distribution costs. Consequently, the transfer of green technology from developed regions to border areas is facilitated, bolstering cross-regional diffusion of innovation. This, in turn, stimulates green innovation within border areas, nurturing the growth of green industries and contributing to carbon emission reduction.

Hypothesis H3: The pilot policy of the "Broadband China" strategy can curtail carbon emission levels in border areas by spurring urban green innovation.

Through the exploration of these hypotheses, this paper aims to illuminate the intricate dynamics linking network infrastructure construction, green technological innovation, and carbon emission

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reduction within border regions.

3. Research Design and Variable Selection

3.1 Modeling Approach

To investigate the influence of network infrastructure construction on carbon emissions within border regions, this study employs the pilot policy of the "Broadband China" strategy as an exogenous policy intervention. The double-difference method is adopted for identification testing. Specifically, the sample comprises cities along the border that have been designated as "Broadband China" pilot cities, constituting the treatment group. Meanwhile, the remaining cities along the border form the control group. Recognizing the policy's approval in three distinct phases, a multi-period double-difference framework is employed. This approach accommodates prior research findings. The econometric model takes the following form:

$$Y_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 X_{it} + \upsilon_t + \mu_i + \varepsilon_{it} \quad (1)$$

Here, the subscripts i and t denote the prefecture-level city and year, respectively. Y_{it} represents the dependent variable—carbon emission level of city i in year t. X_{it} encompasses a set of control variables that could potentially influence the carbon emission levels of each prefecture-level city. υ_t and μ_i denote the time fixed effect and individual fixed effect for each city, correspondingly. ε_{it} signifies the stochastic error term of the equation, while $Policy_{it}$ denotes the random error term. $Policy_{it}$ acts as a binary indicator for "Broadband China" demonstration cities. The coefficient α_1 gauges the impact of network infrastructure construction on carbon emissions. If this coefficient is negative, it implies a detrimental effect on carbon emissions growth, signifying the potential to curb carbon emission expansion. Conversely, a positive coefficient indicates a positive effect.

3.2 Description of Variables

3.2.1 Dependent Variable

The primary focus of this study is the carbon emission level (CE) as the dependent variable. In accordance with prevalent practice in both domestic and international literature, the logarithmic value of carbon emissions is employed to gauge the carbon emission level in each border city. Carbon emissions encompass various sources, including electricity consumption, gas and liquefied petroleum gas (LPG) consumption, transportation, and thermal energy. Following the approach of Wu Jianxin and Guo Zhiyong [10], this study aggregates the carbon emissions resulting from these sources for each border city from 2006 to 2018. The calculation involves: Determining carbon emissions from electricity consumption using regional power grid baseline emission factors and electricity consumption data. Calculating carbon emissions from gas and LPG consumption utilizing relevant conversion factors provided by IPCC2006. Quantifying carbon emissions from transportation energy consumption by considering various energy types and modes of transportation. Deriving carbon emissions from thermal energy consumption through calculations involving boiler thermal efficiency and raw coal combustion.

3.2.2 Core Explanatory Variable

The central explanatory variable in this study is the double-difference term (policy) associated with the "Broadband China" strategy. This term serves as a proxy for network infrastructure construction. The "Broadband China" strategy, introduced by China's State Council in August 2013, was implemented over three successive years, designating 39 pilot cities annually. Among these, the first batch included 6 border cities, the second batch 9, and the third batch 11, making a total of 26 border cities. This study designates a value to each city based on its inclusion in the "Broadband China" pilot city lists. If a city is designated as a "Broadband China" pilot city and its observation period follows the year of selection, it is assigned a value of 1; otherwise, a value of 0.

3.2.3 Control Variables

To mitigate the impact of omitted variables and address endogeneity concerns, this study integrates the following control variables, drawing on existing domestic and international literature: Openness to the outside world (OP): This variable captures a city's trade openness, as it relates to carbon emissions. Foreign direct investment (FDI) and trade openness have been associated with varying carbon emission trends in different economic contexts. This study employs the ratio of actual utilized FDI to Gross

National Product (GNP) as a measure of openness. Financial Development Level (FD): Financial development is known to influence environmental conditions. The degree of financial development can exacerbate environmental degradation in developing countries due to information asymmetry, while in developed countries, it can stimulate clean technology advancement, reducing greenhouse gas emissions. The ratio of year-end financial institution loan balance to GDP is used to gauge financial development. Energy Consumption Level (EG): The relationship between energy consumption and environmental pollution has long been a societal concern. The carbon-intensive nature of China's economic growth highlights the need to address energy consumption. To account for this, the study uses the ratio of total energy consumption to GDP (energy consumption per unit of GDP) as a proxy variable for energy consumption level. Level of Science and Technology Investment (RD): Government investment in science and technology can spur innovation and resource efficiency, subsequently reducing carbon emissions. The proportion of fiscal expenditures allocated to science and technology (RD) is employed to measure the S& T investment level. Employment Structure (ES): Optimizing the employment structure can drive economic transformation and enhance productivity, thereby lowering carbon emissions. The proportion of employment in the tertiary industry serves as a measure of employment structure.

3.3 Data Sources

This study employs panel data encompassing 75 prefecture-level cities located along the border areas for the period spanning 2006 to 2018. The essential data sources used include the China Statistical Yearbook, China Urban Statistical Yearbook, and the statistical bulletins of each respective prefecture-level city. Descriptive statistics for each variable are presented in Table 1.

Table 1: Descriptive statistics of main variables.

Variable	Obs	Mean	S. D.	Min	Max
CE	975	5.802	1.204	2.019	8.616
Policy	975	0.061	0.239	0	1
OP	909	-5.128	1.612	-11.503	-1.591
FD	966	-0.283	0.544	-2.586	1.393
EG	965	-2.782	1.253	-6.797	0.554
RD	975	-5.115	0.783	-8.214	-1.798
ES	975	-0.624	0.388	-9.337	-0.053
INV	975	0.372	0.632	0.003	4.829
IND	975	1.059	2.63	0.094	81.718
AGD	975	0.029	0.0435	0	0.312

4. Empirical Results and Analysis

4.1 Benchmark Regression

Table 2 displays the baseline regression findings of this study, where the focal explanatory variable is the carbon emission level (CE) of each border-level city, and the core explanatory variable is the policy variable tied to the "Broadband China" pilot program. Acknowledging the potential impact of control variables on the coefficients of these core explanatory factors, this research employs the stepwise regression methodology to explore the effects of network infrastructure construction on carbon emissions within border regions. Specifically, the adoption of the stepwise regression approach aims to scrutinize the influence of network infrastructure construction on carbon emissions in border areas. Within Table 2, column (1) exhibits the regression results without the inclusion of any control variables, while columns (2) to (6) progressively introduce control variables, assessing their influence step by step. Notably, all equations exhibit goodness-of-fit values surpassing 0.88, underscoring their strong fit with the data. Across columns (1) to (6) in Table 2, the estimated coefficients linked to the "Broadband China" pilot policy variable consistently display significantly negative values at the 1% level. This robustly indicates that the "Broadband China" pilot policy variables exert a highly substantial negative impact on carbon emissions. This substantiates that the establishment of network infrastructure effectively curtails carbon emissions in border regions. Specifically, the coefficient in column (1) is recorded as -0.313. As control variables are incrementally incorporated, the estimated coefficient progressively rises to approximately 0.421. This trend suggests that the impact of network infrastructure construction on the reduction of carbon emissions in border areas strengthens with the inclusion of control variables. Consequently, H1 is validated, confirming the affirmative effect of network infrastructure construction on diminishing carbon emissions and fostering the development of a low-carbon economy in border regions.

Regarding control variables, the positive coefficient attached to the energy consumption level (EG) indicates that heightened energy consumption intensity corresponds with elevated carbon emission levels in border cities. Conversely, the positive coefficient associated with the science and technology investment level (RD) suggests that advancements in regional science and technology development effectively hinder the escalation of carbon emission levels in the border region. Furthermore, the influences of variables such as the degree of openness to the outside world (OP), the level of financial development (FD), and the employment structure (ES) on carbon emissions are negligible. Worth noting is that the lack of substantial influence from OP, FD, and ES on carbon emissions might be attributed to the less developed status of the border region, characterized by lagging economic progress. Consequently, the potential of economic and financial development, openness, and optimized employment structures to significantly impact carbon emission reduction might not have been fully realized within this context.

Table 2: Baseline regression results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
Policy	-0.313 *** (-3.00)	-0.371*** (-3.79)	-0.405*** (-4.14)	--0.410*** (--4.43)	-0.408*** (-4.46)	-0.421*** (-4.40)
EG		0.429*** (5.04)	0.405*** (4.69)	0.419*** (5.21)	0.421*** (4.84)	0.422*** (4.85)
OP			-0.019 (-0.99)	-0.020 (-1.10)	-0.020 (-1.10)	-0.019 (0.285)
RD				0.158***(3.12)	0.158*** (3.08)	0.154*** (2.99)
FD					-0.030(-0.24)	-0.026 (-0.20)
ES						-0.071 (-1.44)
Cons.	5.821*** (922.73)	7.000*** (29.42)	6.900*** (24.26)	7.74*** (24.33)	7.736*** (24.33)	7.676*** (24.68)
City Fe	YES	YES	YES	YES	YES	YES
Year Fe	YES	YES	YES	YES	YES	YES
Obs.	975	965	902	902	902	902
R^2	0.889	0.915	0.912	0.915	0.906	0.916

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; values in parentheses are t-statistics.

4.2 Parallel Trend Test

The utilization of the multi-period double-difference model hinges on fulfilling the parallel trend test prerequisite. This necessitates that both the experimental group and the control group demonstrate parallel trends prior to the policy implementation. To scrutinize this condition, a dynamic model for hypothesis testing was constructed, as delineated in equation (2).

$$Y_{it} = \beta_0 + \sum_{\delta=-6}^{\delta=-1} \beta_\delta pre_{it} + \beta current_{it} + \sum_{\gamma=1}^{\gamma=4} \beta_\gamma post_{it} + \beta_1 X_{it} + \upsilon_t + \mu_i + \varepsilon_{it} \quad (2)$$

Within this equation, pre_{it} and $post_{it}$ stand as counterfactual binary variables. The former, pre_{it}, signifies the year preceding the enactment of the "Broadband China" strategy's pilot policy, with t values ranging from -1 to -6. Similarly, $post_{it}$ denotes the year succeeding the policy's implementation, with t values spanning from 1 to 6. Additionally, $current_{it}$ designates the policy implementation year, with other variables remaining consistent with the benchmark regression equation. These modifications maintain alignment with the baseline regression equation. Visual representations of urban carbon emission shifts before and after the "Broadband China" pilot policy implementation are illustrated in Figure 1. The graph reveals that confidence intervals for pre2-pre8 values intersect with the horizontal axis, showcasing a generally level trajectory. This observation underscores the absence of divergence between pilot and non-pilot cities prior to policy implementation. Conversely, confidence intervals for post1-post4 values lack intersections with the horizontal axis, accompanied by a gradual descent from the horizontal axis. This distinct pattern signifies a significant discrepancy between pilot and non-pilot

ISSN 2522-3488 Vol. 7, Issue 7: 21-33, DOI: 10.25236/IJNDES.2023.070704

cities following policy implementation, manifesting in noteworthy changes in carbon emissions. This implies that a substantial post-policy implementation reduction in carbon emissions occurs in pilot cities compared to non-pilot cities. The discernible outcomes from the temporal trend graph affirm the fulfillment of the double-difference method's parallel trend test hypothesis. The successful passage of the parallel trend test corroborates the reasonableness and efficacy of the double-difference method's results.

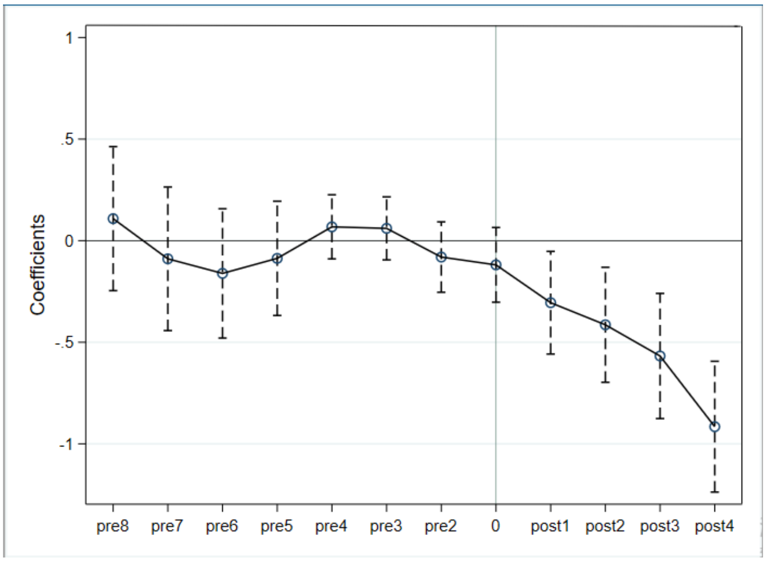

Figure 1: Results of parallel trend test

4.3 Placebo Test

While the preceding study diligently controlled for urban characteristic factors that influence carbon emission levels along the border area, it remains possible that certain characteristics, varying over time and location, evade observation. These unobservable factors could potentially impact the model's estimation outcomes and introduce bias to the final results. To address this concern, this paper employs a placebo test, a method widely adopted in existing literature. Concretely, the placebo test involves the random selection of "Broadband China" pilot cities from the experimental group sample. These cities are then subjected to regression using the baseline regression model. This procedure is iterated 500 and 1,000 times, yielding 500 and 1,000 estimated coefficients respectively. The results of these iterations are depicted in Figure 2 and Figure 3.

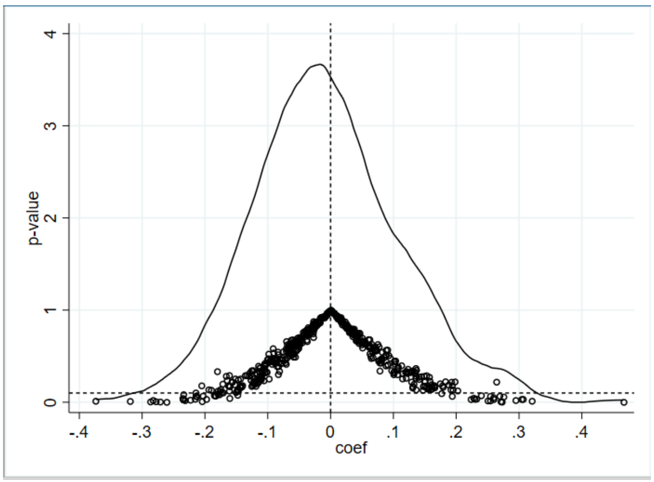

Figure 2: Placebo test repeat sampling 500 times

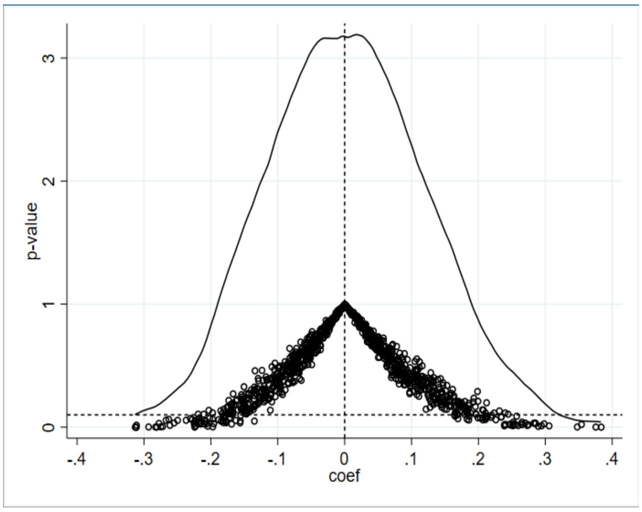

Figure 3: Placebo test repeat sampling 1000 times

Looking at the figures, it's evident that the kernel density plot and P-value distribution plot for the estimated coefficients, both for 500 and 1000 iterations, exhibit a close approximation to a normal distribution. Additionally, the majority of estimated coefficients cluster around the vicinity of 0. In contrast, the actual estimated coefficients hover around -0.31. This significant deviation from chance indicates that the observed outcomes are not coincidental. This affirmation dismisses the possibility that external unobservable factors might influence the inhibition effect of the "Broadband China" policy on carbon emissions in the coastal region. Consequently, we can confidently assert that the inhibitory impact of the "Broadband China" policy on carbon emissions in the border area is not confounded by other hidden variables. This outcome contributes to elevating the reliability and robustness of the estimation results.

4.4 Robustness test

To bolster the dependability of the preceding model's regression outcomes and to mitigate the potential bias arising from outliers and endogeneity effects, this study is committed to undertaking a series of rigorous robustness tests. These tests encompass diverse methodologies, including the utilization of the propensity score-matched double-difference method (PSM-DID), substitution of explanatory variables, culling out outliers, and forestalling the impact of non-random factors by introducing interaction terms between specific urban factors and policies. Moreover, the tests encompass the exclusion of confounding factors through the introduction of interaction terms between province and year, as well as the removal of extraneous policy variables that could interfere with the accuracy of the estimation outcomes.

4.4.1 PSM-DID Estimation

Given the non-random selection process of pilot cities under the "Broadband China" policy, discrepancies in initial conditions between the experimental and control groups may introduce selection bias to the estimation results. To mitigate this issue, this paper employs propensity score matching (PSM) to harmonize samples from both groups. This entails retaining samples with comparable initial conditions, except for carbon emission levels, ensuring that cities in the control group possess the same likelihood of becoming "Broadband China" pilot cities as those in the experimental group. All five control variables in the model are employed as covariates for matching, with the matching outcomes detailed in Table 3. Notably, the standard errors of the matched covariates remain within 10%. Among them, the P-values for the four covariates—OP, ES, FD, and RD—shift from significant to non-significant post-matching. Additionally, the P-value for EG rises from 0.653 to 0.757. These findings signify that, following matching, the experimental and control groups exhibit minimal divergence, thereby fulfilling the necessary conditions for the PSM-DID method's estimation.

The PSM-DID regression results are presented in the first column of Table 4, comprising a total of 627 matched observations. Among these, the impact coefficient of the "Broadband China" policy on the carbon emission level is -0.353, signifying statistical significance at the 0.01 level. This outcome underscores the substantial negative effect of network infrastructure construction on the level of carbon emissions in the coastal region and further enhances the robustness of the conclusion.

Table 3: Results of propensity score matching.

Variable	Sample matching	Mean		S.D.(%)	Reduction in S.D.(%)	T-Value	P-Value
		Experimental group	Control group				
OP	Before	-4.839	-5.231	24.1	92.4	3.23	0.001
	After	-4.825	-4.855	1.8		0.20	0.838
ES	Before	-0.744	-0.594	-31.0	93.5	-5.07	0.000
	After	-0.687	-0.696	2.0		0.38	0.708
FD	Before	-0.409	-0.251	-26.7	88.9	-3.80	0.000
	After	-0.379	-0.396	3.0		0.34	0.734
EG	Before	-2.764	-2.722	-3.2	12.9	-0.45	0.653
	After	-2.803	-2.766	-2.8		-0.31	0.757
RD	Before	-4.753	-5.211	58.6	95.9	7.88	0.000
	After	-4.791	-4.810	2.4		0.27	0.786

4.4.2 Remaining Robustness Tests

To ensure the continued robustness of the estimation results, this paper employs various additional tests to validate the conclusions. These tests involve substituting explanatory variables, removing outliers, introducing interaction terms between city-specific factors and policy variables, incorporating interaction terms between province and year, and considering other policy variables. The outcomes are displayed in Columns (2) to (8) of Table 4. Column (2) showcases the results following the replacement of explanatory variables in the baseline regression model. The choice here is to employ the logarithmic value of carbon emissions from prefectures within each border region to represent carbon emission levels, drawing inspiration from existing literature [11-12]. Carbon intensity is adopted as a proxy for carbon emission levels, further confirming the resilience of the conclusions. The calculated carbon emission intensity is obtained by dividing carbon emissions by the GDP of each prefecture-level city within the border region. The regression results indicate an estimated coefficient of -0.262 for the "Broadband China" policy variable, with statistical significance at the 5% level, thus confirming the robustness of the conclusions even with the replacement of explanatory variables.

To address the issue of non-randomness in selecting pilot cities for the "Broadband China" policy, non-random effects can also be controlled by introducing various economic and geographic characteristics of cities as well as interaction terms involving policy variables. This refinement is based on the baseline regression equation and is presented in Equation (3):

$$Y_{it}=\alpha_0+\alpha_1 Policy_{it}+D_i\times policy_{it}+\alpha_2 X_{it}+\upsilon_t+\mu_i+\varepsilon_{it} \quad (3)$$

D_i represents five economic geographic characteristics, including longitude, latitude, topographic relief, whether the city is part of the Yangtze River Economic Belt, and whether it is a provincial capital city. Column (3) illustrates the regression results reflecting this approach. The findings reveal that even after accounting for non-random factors, the estimated coefficients of the "Broadband China" pilot policy variables remain significantly negative at the 1% level, underscoring the robustness of the conclusions.

The presence of extreme values in the sample may lead to considerable deviations in estimated coefficients. Column (4) demonstrates the regression results following the implementation of the winsor command at the 1% level, which involves trimming the tails. The estimated coefficient for the "Broadband China" pilot policy variable is -0.408, slightly lower than the baseline regression yet still significantly negative at the 1% level. This underscores the robustness of the outcomes, even after removing outliers from the sample.

Given that various border provinces may have introduced distinct policies aimed at carbon emission reduction during the 2006-2018 period, resulting in differing emission level trends across provinces, these factors can potentially confound the effects of the policies under study. To address this concern, an interaction term between province fixed effects and time fixed effects is incorporated into the baseline regression model, as depicted in Equation (4):

$$Y_{it}=\alpha_0+\alpha_1 Policy_{it}+\alpha_2 X_{it}+\upsilon_t\times\rho_s+\mu_i+\varepsilon_{it} \quad (4)$$

Here, ρ_δ signifies the province fixed effect. Column (5) illustrates the results after accounting for this confounding factor. Notably, the sign and significance of the estimated coefficients for pilot cities under the "Broadband China" policy remain consistent. This indicates that the inhibitory effect of

ISSN 2522-3488 Vol. 7, Issue 7: 21-33, DOI: 10.25236/IJNDES.2023.070704

network infrastructure construction on carbon emissions is robust.

China's implementation of other pilot policies during the 2006-2018 period may have influenced carbon emission levels in cities. To mitigate this potential interference, this paper further controls for the effects of smart city pilot and low-carbon pilot policies on border region carbon emission levels. The outcomes are presented in Columns (6) to (8). These columns illustrate the results of separately controlling for the smart city pilot and low-carbon pilot policies, and Column (8) displays the results after controlling for both policies simultaneously. The findings reveal that, even after accounting for the impacts of these two policies, the reduction in emissions due to network infrastructure construction remains relatively robust.

Table 4: Robustness test results.

Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Policy	-0.353^{***} (-3.69)	-0.262^{**} (-2.95)	-0.391^{***} (-4.14)	-0.408^{***} (-4.63)	-0.359^{***} (-3.88)	-0.419^{***} (-4.40)	-0.418^{***} (-4.38)	-0.417^{***} (-4.12)
Longitude			0.0004 (0.80)					
Latitude			-0.0012 (-1.49)					
Topographic Relief			0.033^{***} (3.27)					
Cities in Yangtze Economic Belt			-0.006 (-0.20)					
Provincial Capital Cities			-0.029 (-1.83)					
Prov#year					-0.011^{***} (-5.16)			
Smart Cities						-0.076 (-0.94)		-0.083 (-1.05)
Low Carbon Pilot							-0.050 (0.70)	-0.058 (-0.82)
Control	YES	YES	YES	YES	YES	YES	YES	YES
City Fe	YES	YES	YES	YES	YES	YES	YES	YES
Year Fe	YES	YES	YES	YES	YES	YES	YES	YES
Obs	627	902	902	902	902	902	902	902
R^2	0.904	0.935	0.924	0.920	0.921	0.916	0.916	0.916

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; values in parentheses are t-statistics.

5. Analysis of Heterogeneity

The preceding study has illustrated the role of network infrastructure construction in lowering carbon emission levels in border regions using various methods. However, there are variations in urban characteristics, such as geographic location and economic development level, among different cities. These variations might lead to varying impacts of the "Broadband China" policy pilots. Therefore, this paper delves into the potential regional heterogeneity of the impacts of the "Broadband China" policy pilots.

The study of regional heterogeneity can be categorized in two ways. One approach involves classifying regions based on the traditional division of the eastern, central, and western regions, resulting in the division of cities into eastern, central, and western categories. Alternatively, the study can classify regions according to their geographic locations along the borders, specifically the northeastern border region, the northern border region, and the southwestern border region. The northeastern border region encompasses Heilongjiang, Jilin, and Liaoning provinces. The southwestern border region includes Guangxi, Yunnan, and Tibet provinces. Similarly, the northern border region comprises Xinjiang, Gansu, and Inner Mongolia provinces. For the purpose of this paper, the sample from the southwestern border region is limited to all prefecture-level cities within Guangxi and Yunnan provinces, due to the unavailability of sufficient data on Tibet.

Table 5 presents the results of the regional heterogeneity analysis. Columns (1) to (2) display regression outcomes based on the East-Middle-West division, while columns (4) to (6) show results based on the border cities' geographical location. The findings indicate that the policy variable coefficients in columns (1) to (3) are all negative, revealing the significant carbon emission reduction effect of network infrastructure development in both East and Midwest border cities. However, differences in policy effects exist. In terms of coefficient magnitudes, the carbon emission reduction effect is more pronounced in central and western border cities compared to eastern border cities. This might stem from the fact that network infrastructure development in the eastern region is more mature, potentially leading to redundancy in construction and higher energy consumption and carbon emissions. On the other hand, central and western regions have the opportunity to adopt advanced technology to avoid unnecessary emissions. Estimated coefficients in columns (3) to (5) are all negative, with significant P-values for cities along the Northeast and North borders (at 5% and 1% levels), but not for the Southwest. This indicates that network infrastructure construction significantly reduces carbon emissions in cities along the Northeast and North borders, but not as much in the Southwest. In terms of coefficient magnitudes, the effect of network infrastructure construction on carbon emission reduction is more pronounced in cities along the northern border than in cities along the eastern border. This could be due to cities along the northern border being more distant from developed regions, thus benefiting more from the reduction in people movement and transportation through digital services. Meanwhile, cities along the northeastern border have likely already implemented digital substitution to a significant extent, resulting in a weaker carbon reduction effect due to reduced room for further substitution.

Table 5: Analysis of regional heterogeneity.

Variable	Eastern city	Central and western cities	Northeast border cities	Northern border cities	Southwest border cities
	(1)	(2)	(3)	(4)	(5)
Policy	-0.287** (-2.61)	-0.394** (-3.81)	-0.222*** (-3.05)	-0.703** (-2.63)	-0.088 (-0.85)
Control	YES	YES	YES	YES	YES
City Fe	YES	YES	YES	YES	YES
Year Fe	YES	YES	YES	YES	YES
Obs	181	721	425	208	269
R^2	0.933	0.907	0.974	0.903	0.925

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; values in parentheses are t-statistics

6. Analysis of Influence Mechanism

Network infrastructure can also impact carbon emission levels by influencing urban green innovation and industrial structure upgrading. To examine the existence of this mechanism, a mediation effect model is established, as demonstrated in equations (5) and (6).

$$M_{it} = \alpha_0 + \alpha_1 Policy_{it} + \alpha_2 X_{it} + \upsilon_t + \mu_i + \varepsilon_{it} \quad (5)$$

$$Y_{it} = \alpha_0 + \alpha_1 Policy_{it} + \theta M_{it} + \alpha_2 X_{it} + \upsilon_t + \mu_i + \varepsilon_{it} \quad (6)$$

Here, M_{it} represents the mechanism variables of green science and technology innovation level and industrial structure upgrading level in this study.

Table 6 presents the results of testing the impact mechanism of the "Broadband China" policy pilot on carbon emissions in border areas. The estimated coefficients of the "Broadband China" pilot policy in columns (1) and (3) are 0.262 and 0.426, respectively, with P-values significantly positive at the 10% and 1% levels. This indicates that network infrastructure construction can notably enhance the upgrading of industrial structures and the advancement of green science and technology innovation in coastal regions. Similarly, the estimated coefficients of the "Broadband China" pilot policy in columns (2) and (4) are also 0.262 and 0.426, respectively. Columns (2) and (4) incorporate industrial structure upgrading, green science and technology innovation level, and "Broadband China" policy pilot variables in the regression. The results reveal significantly negative coefficients for IND, INV, and policy, suggesting that industrial structure upgrading and green science and technology innovation effectively restrain carbon emissions. Furthermore, network infrastructure construction can foster industrial structure upgrading, thereby promoting carbon emission reduction. These findings demonstrate that both industrial structure upgrading and green technology innovation effectively mitigate carbon emissions, while network infrastructure construction contributes to carbon emission reduction in border areas by stimulating industrial structure upgrading and green technology innovation. In this context, industrial structure upgrading and green technology innovation serve as partial intermediaries, thereby verifying H2 and H3.

Table 6: Results of Mechanism Tests.

Variable	IND	CE	INV	CE
	(1)	(2)	(3)	(4)
Policy	0.262** (2.12)	-0.380*** (-3.95)	0.426** (2.50)	-0.377*** (-4.07)
IND		-0.156* (-1.79)		
INV				-0.104** (-2.21)
Control	YES	YES	YES	YES
City Fe	YES	YES	YES	YES
Year Fe	YES	YES	YES	YES
Obs.	902	902	902	902
R^2	0.792	0.916	0.732	0.916

Note: *** indicates $p < 0.01$, ** indicates $p < 0.05$, * indicates $p < 0.1$; values in parentheses are t-statistics.

7. Conclusions and policy recommendations

Promoting network infrastructure construction and achieving the objectives of "carbon peak" and "carbon neutrality" have emerged as a new consensus and initiative in advancing the high-quality economic development of China's border regions in the modern era. Leveraging city-level data from China's border regions spanning from 2006 to 2018, this study investigates the influence and underlying mechanisms of network infrastructure construction on carbon emissions within these border regions. Employing the double-difference methodology and using the "Broadband China" city policy as an entry point, the research arrives at the following key findings. Firstly, the implementation of the "Broadband China" initiative substantially diminishes urban carbon emissions, and this outcome remains consistent even after undergoing a battery of robustness tests. Secondly, the mechanism analysis unveils that the advancement of green technological innovation and the optimization of industrial structure serve as principal pathways through which network infrastructure construction impacts carbon emissions within border regions. Thirdly, heterogeneity analysis underscores regional variations in the influence of "Broadband China" city development on carbon emissions within the border areas. This variance is particularly manifested by the larger reduction in carbon emissions resulting from network infrastructure construction in the central and western border regions, compared to the eastern regions. Additionally, the effect of network infrastructure construction on carbon emission reduction is significant in the northeastern and northern border areas, while this impact is not yet evident in the southwestern border region. Based on these insights, this paper presents the following policy recommendations:

Firstly, the empirical results underscore that the construction of network infrastructure significantly diminishes carbon emissions in border regions. This impact implies that network infrastructure construction not only enhances economic welfare by fostering economic efficiency but also bolsters social welfare by curbing carbon emissions. In recent years, the digital economy has emerged as a pivotal driver of economic and societal transformation. However, in comparison to developed nations, China's network infrastructure construction remains relatively underdeveloped, particularly in the less developed border areas where progress lags behind the eastern coastal cities. Hence, it is imperative for China to augment investments in network infrastructure within these border regions. This endeavor should entail a meticulous analysis of successful experiences that can be replicated, leading to an expansion of the "Broadband China" strategy's pilot program. By tailoring this expansion to suit regional specifics, the overarching goal is to expedite the realization of the strategy, thereby accelerating the digitalization advancement within these border areas. Secondly, a mechanistic analysis of the outcomes highlights that the reduction in carbon emissions resulting from the "Broadband China" demonstration city program is attributed to its facilitation of green technological innovations and the optimization of industrial structures. This underscores the importance of ensuring that network infrastructure planning and design in border cities explicitly support emerging enterprises, thereby

ISSN 2522-3488 Vol. 7, Issue 7: 21-33, DOI: 10.25236/IJNDES.2023.070704

encouraging their clustering and fostering the enhancement and evolution of the industrial landscape. Through the establishment of innovation service platforms and similar measures, the potential for knowledge diffusion and spillover effects from digital infrastructure can be maximized. Thirdly, the findings of the heterogeneity analysis reveal that the effects of network infrastructure construction on carbon emissions vary across different regions. Given the limited impact of network infrastructure on curbing carbon emissions in the southwestern border region, it becomes necessary for the government to adopt an approach that considers the distinct developmental attributes of each city. By implementing dynamic and tailored policies, network infrastructure can be established as a fundamental prerequisite for effectively mitigating regional developmental imbalances.

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