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Low-carbon production and corporate biodiversity concern: Evidence from Chinese manufacturing firms

Cong Nie, Chen Zhang *

Economics and Management School, Wuhan University, Wuhan, PR China

A R T I C L E I N F O

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A B S T R A C T

Carbon emissions threaten biodiversity, but manufacturing firms often neglect this concern. This study examines the impact of China's Low-Carbon City Pilot on manufacturing firms' biodiversity concern using a staggered difference-in-differences model. We use financial data from Chinese publicly listed A-share manufacturing firms, with biodiversity concern measured by the frequency of related terms per 10,000 words in annual reports. We find that the policy significantly increases enterprises' biodiversity attention, particularly for firms with greater financing constraints, and enhances environmental performance and corporate financing. Robustness tests, including heterogeneity-robust estimators, confirm the validity of our findings. The study highlights important implications for policymakers and industry stakeholders, suggesting that integrating biodiversity considerations into policy frameworks and business strategies could enhance both environmental and economic outcomes.

1. Introduction

Planet Earth is experiencing a biodiversity crisis, with the World Wildlife Fund (WWF) reporting a 73 % decline in the average size of wildlife populations monitored over the past 50 years.[1] This biodiversity loss disrupts supply chains, raises operational costs, and heightens the instability of natural resource availability (Green et al., 2019; Kumar, 2012). Manufacturing carbon emissions exacerbate climate change, which accelerates biodiversity loss (Botkin et al., 2007; Omann et al., 2009). Reducing emissions can help mitigate environmental damage, diminish the impact on biodiversity, and support long-term business sustainability (Venter et al., 2009).

Although the environmental significance of biodiversity is increasingly recognized, manufacturing industries have traditionally paid less attention to this issue than primary sectors that depend directly on biodiversity for resources, productivity, and stability (He et al., 2024). In contrast, manufacturing has emphasized biodiversity preservation less as the negative externalities of the sector's activities are not reflected in production costs, which limits the incentives to address biodiversity concerns.

How can the manufacturing sector be encouraged to prioritize biodiversity and improve environmental performance? Given that excessive carbon emissions are one of the ways in which manufacturing affects biodiversity, this study examines whether policies to reduce carbon emissions in production can increase biodiversity awareness among manufacturers, and if so, whether this heightened

* Corresponding author at: Economics and Management School, Wuhan University, Luojia Hill, Wuhan 430072, PR China.
E-mail address: zhangchen34349@whu.edu.cn (C. Zhang).

[1] The data measured by the Living Planet Index are provided by WWF's 2024 Living Planet Report. See https://www.worldwildlife.org/publications/2024-living-planet-report.

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awareness translates into improved environmental performance.

Specifically, we examine the impact of China's Low-Carbon City Pilot (LCCP) policy on manufacturing firms' biodiversity concern. Launched in three waves (2010, 2012, and 2017), the policy supported China's commitment to achieving peak carbon emissions by 2030 and carbon neutrality by 2060. The LCCP primarily targets the production side of the economy by promoting industrial structure optimization, strengthening environmental enforcement, and enhancing technological innovation capabilities.

This study focuses on manufacturing firms listed on the Shanghai and Shenzhen A-share markets using financial data from 2007 to 2022. We use the biodiversity concern index developed by He et al. (2024), which quantifies the proportion of biodiversity-related keywords in enterprises' annual reports to measure corporate concern for biodiversity. Given the three-wave rollout of the LCCP policy, we employ a staggered difference-in-differences (DID) model to analyze the policy's impact on manufacturing firms' biodiversity concern.

The results indicate that LCCP implementation significantly enhanced firms' attention to biodiversity, and this effect remains robust after addressing potential biases using the heterogeneity-robust estimator (Callaway and Sant'Anna, 2021). A key finding is that the policy's impact is stronger for firms with greater financing constraints, indicating that these firms may prioritize biodiversity concerns to improve their financing access. Additionally, firms with a stronger focus on biodiversity tend to consider improving overall environmental, social, and corporate governance (ESG) performance (particularly in the environmental dimension) and gain better access to financing such as long-term borrowing and bank loans, indicating that biodiversity considerations may facilitate corporate financing.

This study makes two key contributions. First, it extends the research on the effects of LCCP implementation. At the macro level, the LCCP has enhanced green total factor productivity (GTFP) in pilot cities through technological advancements, industrial upgrading, and efficient resource allocation (Qiu et al., 2021), while reducing annual CO2 emissions by 2.6% (Wang et al., 2023). At the firm-level, it has improved energy-intensive firms' GTFP by increasing bank credit supply, fostering research and development and fixed asset investment (Huwei et al., 2023), and enhancing carbon emissions efficiency by about 1.7 % (Yu and Zhang, 2021). Second, the study contributes to the literature on corporate biodiversity. While previous studies focus on investor perspectives, fewer have examined how to strengthen firms' biodiversity concern. Companies are increasingly integrating biodiversity conservation into environmental practices for social legitimacy and external recognition (Boiral and Heras-Saizarbitoria, 2017). Institutional investors reward biodiversity disclosures (Ali et al., 2023); however, many firms still primarily perceive biodiversity as a reputational risk rather than a core responsibility (Smith et al., 2019), highlighting the need for further research.

The remainder of this paper is structures as follows. Section 2 details the data and identification strategies, Section 3 presents the baseline empirical results and robustness tests, and Section 4 concludes by summarizing the key findings.

2. Data and empirical strategy

The sample for this study includes A-share manufacturing firms publicly listed in China, covering 2007–2022. Since the study examines the impact of LCCP implementation in three waves (2010, 2012, and 2017), we use a staggered DID model, with firms in pilot cities assigned to the treatment group and the remaining firms in the control group. The biodiversity concern index from He et al. (2024), is based on text analysis using the biodiversity dictionary from Giglio et al. (2023).[2] Text mining was conducted on the annual reports of listed companies, and the index was calculated by dividing the character count of biodiversity-related terms by reports' total character count, yielding a firm-year measure of biodiversity concern. We use the dataset provided by He et al. (2024), defining the biodiversity concern index as the frequency of biodiversity-related terms per 10,000 words in annual reports. All financial data are sourced from the China Stock Market & Accounting Research database.

To evaluate the effect of LCCP implementation on firms' biodiversity concern, we employ a DID approach with a standard two-way fixed effects (TWFE) model. The empirical model is represented as follows:

$$Y_{i,c,t} = \alpha_0 + \alpha_1 LCCP_{c,t} + \alpha_2 Firm\ controls_{i,t} + \alpha_3 City\ controls_{c,t} + \lambda_i + \mu_t + \varepsilon_{i,c,t} \quad (1)$$

where $Y_{i,c,t}$ represents the biodiversity concern index for firm *i* in city *c* on year *t*. We construct a dummy variable ($LCCP_{c,t}$) that equals one if firm *i* is located in a pilot city and the fiscal year occurs after LCCP implementation. $Firmcontrols_{i,t}$ denotes firm-level attributes, encompassing size, leverage, return on assets, cash-to-assets ratio, state-owned enterprise status, female director ratio, independent director ratio, board size, and largest shareholder ownership. $Citycontrols_{c,t}$ denotes city-level variables, encompassing per capita gross domestic product (GDP), the share of GDP from secondary industries, and the city's population. The variable definitions are presented in Appendix Table A.1, and summary statistics are detailed in Table 1. We include firm fixed effects (FE) (λ_i) and year FE (μ_t). $\varepsilon_{i,c,t}$ denotes the error term, and standard errors are clustered at the city-year level.

[2] The dictionary includes terms such as biodiversity, coral, desertification, fauna, ecosystems, aquatic, species, flora, habitat, carbon sinks, wetlands, marine, biosphere, deforestation, wildlife, ecosphere, and ecology.

Table 1
Summary statistics.

Variable	Obs	Mean	Std. Dev.	P5	P50	P95
Biodiversity Concern	23,171	0.640	2.322	0	0.182	2.123
Size	23,171	21.946	1.224	20.291	21.785	24.269
Lev	23,171	0.385	0.245	0.019	0.385	0.779
ROA	23,171	0.039	0.414	−0.060	0.043	0.142
Cash	23,171	0.215	0.153	0.046	0.171	0.537
SOE	23,171	0.327	0.469	0	0	1
Female	23,171	0.149	0.132	0	0.111	0.429
Indep.	23,171	0.375	0.055	0.333	0.333	0.455
lnBoard	23,171	2.118	0.197	1.792	2.197	2.398
Top1	23,171	34.250	14.635	13.520	32.070	60.730
lnGDPpc	23,171	11.345	0.604	10.186	11.418	12.119
Ind.Share	23,171	42.405	10.861	22.070	43.600	58.240
lnPop.	23,171	6.378	0.675	5.215	6.431	7.292

Note: This table presents the descriptive statistics of variables for the full sample of 2520 individual firms for a total of 23,171 firm-year observations. The variables presented in this table are defined in Appendix Table A.1.

3. Results

3.1. Baseline results

Table 2 presents the baseline results derived from Eq. (1). Columns (1)–(3) focus on firms in the manufacturing sector. In column (1), we include only the TWFE without controlling for any covariates. In column (2), firm-level covariates are introduced, and in, city-level covariates are included in column (3). The results indicate that the LCCP policy significantly increases manufacturing firms' biodiversity concern. Specifically, column (3) shows that the average frequency of biodiversity-related terms in annual reports per 10,000 words rises by 0.081, representing a 12.8% increase relative to the average level in the control group and corresponds to approximately 4.8% of the standard error.

Columns (4)–(6) extend the analysis to firms in other sectors, using similar specifications with progressively added control variables. These columns incorporate industry-year FE to account for differing time trends across industries. The results in columns (4) and (5) show a marginally significant decline in biodiversity concern in other industries correlated with LCCP implementation; however, this effect disappears after introducing all control variables in column (6), indicating no substantial impact. This comparison indicates that while manufacturing firms integrate biodiversity considerations in response to carbon emissions policies, firms in other industries do not.

Considering that the dependent variable is count-based, with 35% of observations at zero, using ordinary least squares (OLS) or a log transformation would introduce bias; therefore, we employ a FE Poisson model (Cohn et al., 2022), presenting results in columns (1)–(3) of Appendix Table A.2, which remain consistent with the baseline findings. Additionally, biodiversity concern varies across manufacturing subindustries, with C20 (Processing of Wood, Bamboo, Rattan, Palm, and Straw Products) exhibiting the highest levels and C23 (Printing and Record Medium Reproduction) the lowest. To account for this variation, we include subindustry-year FE, and results in columns (4)–(6) of Appendix Table A.2 remain robust.

3.2. Heterogeneity-robust estimator

The TWFE estimator in a staggered DID model may be biased due to forbidden comparisons (between units treated at different times) (Goodman-Bacon, 2021), potentially leading to negative weighting. We first apply the methodology proposed by Goodman-Bacon to diagnose this issue. This approach decomposes the TWFE estimator into a weighted average of multiple two-period-by-two-group DID estimates, allowing the identification of forbidden comparisons. Fig. 1 presents the Goodman-Bacon decomposition, where black crosses indicate the weights from forbidden comparisons. While valid comparisons predominate, 12.7 % of the estimates have negative weights, confirming the need for heterogeneity-robust methods to correct bias.

We apply the Callaway and Sant'Anna (2021) DID (CSDID) approach, which uses never-treated or not-yet-treated units as the control group to eliminate forbidden comparisons and provide unbiased ATT estimates. Additionally, the CSDID method incorporates propensity score matching using baseline covariate values. Table 3 presents the re-estimation of Table 2 using CSDID. Not-yet-treated units are included in the control group in columns (1)–(3), whereas columns (4)–(6) use only never-treated units. The specifications remain consistent with the baseline regressions, and the ATT is significant across all columns. For instance, in columns (3) and (6), which include all covariates, LCCP implementation increases biodiversity-related terms in annual reports by 0.264 and 0.279 per 10, 000 words, respectively, both of which exceed the baseline results, validating the robustness of our baseline findings to heterogeneity-robust estimators.

3.3. Parallel trend and placebo tests

In Fig. 2, the event study graph illustrates the dynamic effects before and after treatment. Panel (a) presents the dynamic effects

Table 2
Baseline regressions.

Dep. Var.	Biodiversity concern					
	Manufacturing			Non-Manufacturing		
	(1)	(2)	(3)	(4)	(5)	(6)
LCCP	0.088**	0.095***	0.081**	−0.134*	−0.128*	−0.080
	(0.035)	(0.035)	(0.037)	(0.078)	(0.078)	(0.082)
Size		0.107***	0.108***		0.160***	0.164***
		(0.014)	(0.014)		(0.024)	(0.025)
Lev		0.021	0.025		0.223**	0.225**
		(0.048)	(0.048)		(0.105)	(0.104)
ROA		0.010	0.010		0.000***	0.000***
		(0.008)	(0.008)		(0.000)	(0.000)
Cash		−0.245***	−0.247***		−0.342***	−0.323**
		(0.070)	(0.070)		(0.130)	(0.131)
SOE		0.078**	0.081**		0.098	0.086
		(0.037)	(0.037)		(0.105)	(0.106)
Female		0.083	0.083		0.184	0.195
		(0.073)	(0.073)		(0.203)	(0.203)
Indep		0.218	0.213		−0.161	−0.164
		(0.261)	(0.261)		(0.379)	(0.379)
lnBoard		0.134	0.135		0.056	0.074
		(0.094)	(0.094)		(0.181)	(0.182)
Top1		0.005***	0.005***		0.000	0.000
		(0.001)	(0.001)		(0.002)	(0.002)
lnGDPpc			0.096**			−0.261*
			(0.044)			(0.153)
Ind.Share			−0.007***			0.025***
			(0.002)			(0.008)
lnPop			0.003			0.298
			(0.046)			(0.193)
Firm FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Industry-year FE				✓	✓	✓
#Obs	23,359	23,182	23,171	15,469	15,136	15,136
#Clusters	3202	3194	3183	2067	2064	2064
Adjusted R^2	0.833	0.834	0.834	0.849	0.850	0.851
$\overline{Y}$ of control group	0.633	0.634	0.633	1.292	1.292	1.292

Note: This table presents the results from the ordinary least squares (OLS) regressions analyzing the impact of LCCP policy implementation on biodiversity concern. Standard errors clustered at the city-year level are in parentheses. *, **, and *** denote significance at 10%, 5%, and 1% levels, respectively.

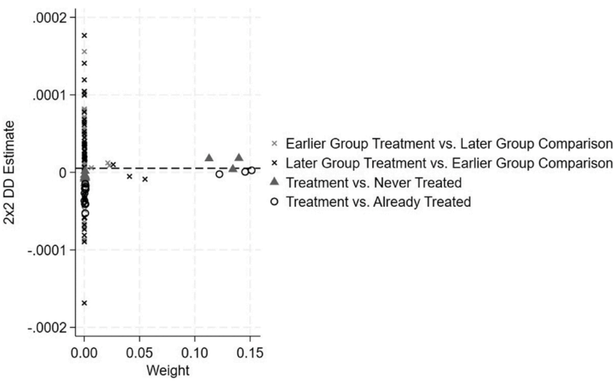

Fig. 1. Goodman-Bacon decomposition.
Note: This figure presents the Goodman-Bacon decomposition (2021) of the TWFE estimator in our staggered DID setting, which breaks down the overall treatment effect into weighted 2 × 2 DID comparisons, separating valid (earlier-treated vs. never/later-treated) and potentially biased (later-treated vs. earlier-treated) comparisons. Each point represents an estimate, and black crosses indicate forbidden comparisons.

using TWFE estimators, using the year prior to LCCP implementation as the reference. Before the policy, no significant differences in biodiversity concern were evident between firms in pilot and nonpilot cities. The impact of the policy became evident approximately three periods after implementation, indicating a gradual increase. Panel (b), using CSDID estimators, exhibits a similar pattern,

Table 3
CSDID estimations.

Dep. Var.	Biodiversity concern					
	Not-yet-treated			Never-treated		
	(1)	(2)	(3)	(4)	(5)	(6)
ATT	0.177*	0.182**	0.264***	0.193**	0.193**	0.279***
	(0.091)	(0.085)	(0.099)	(0.094)	(0.088)	(0.107)
Firm controls		✓	✓		✓	✓
City controls			✓			✓
#Obs	15,701	15,648	15,632	15,695	15,641	15,625

Note: ATT denotes the average treatment effect on treated firms. Doubly robust DID estimators that combine stabilized inverse probability weighting with OLS are presented in this table. In columns (1)–(3), not-yet-treated units are included in the control group, and columns (4)–(6) use only never-treated units. Standard errors clustered at the city-year level are in parentheses. *, **, and *** denote significance at 10%, 5%, and 1% levels, respectively.

confirming parallel trends prior to the policy and widening differences afterward.[3] These results support the parallel trend assumption within the timeframe.

We also conduct a mixed placebo test by randomly assigning placebo treatment timings and units while preserving the cohort structure, repeating this randomization 500 times to generate a distribution of placebo estimators for the $LCCP_{c,t}$ variable. The results reveal that the actual estimated value falls in the 95th percentile, indicating that the observed treatment effects are unlikely to be driven by random variation. Fig. 3 illustrates this result.

3.4. Heterogeneity analysis

Previous research has indicated that corporate concern for biodiversity is often influenced by financing constraints, with financially constrained firms more likely to prioritize biodiversity (McNeely, 1993). In contrast, firms with greater financial capacity are generally better positioned to address social responsibility issues beyond day-to-day operations. This raises the question of whether firms with different financing constraints respond differently to low-carbon production policies.

We differentiate between state-owned enterprises (SOEs) and non-SOEs as these entities face different financing constraints. With soft budget constraints, SOEs are generally more capable and willing to respond to government policies (Lin and Tan, 1999). In Panel (a) of Fig. 4, we separately plot the coefficients estimated from the baseline specification for non-SOE and SOE manufacturing firms. The results demonstrate that LCCP implementation significantly increased biodiversity concern for non-SOEs, whereas no such effect is observed for SOEs.

We also use the Whited and Wu (2006) index as a measure of financial constraints, with a higher index indicating greater financial constraints. Using the 25th, 50th, and 75th percentiles of the Whited-Wu Index, we categorize firms into four groups and separately estimate the policy effects within each group in Panel (b) of Fig. 4. The findings reveal that the LCCP significantly increased biodiversity concern among firms with a Whited-Wu Index between the 50th and 75th percentiles but had no effect on those with lower constraints. A positive but insignificant policy effect is evident among firms above the 75th percentile. These results suggest that concern for biodiversity is influenced by financing constraints, highlighting the influence of external pressure on increasing corporate attention to biodiversity, which is consistent with existing literature (Maurel and Pernet, 2021).

Finally, we categorize firms into four groups based on the 25th, 50th, and 75th percentiles of firm size as defined in Table A.1 in Panel (c) of Fig. 4, using the same specification as the baseline regression to estimate the policy effects within each group. The results reveal that the policy effect is most significant for firms between the 25th and 50th size percentiles, and no significant effects are observed for firms outside this range, indicating that the policy is insufficient to drive biodiversity concern among firms that are either too large or too small.

3.5. Environmental performance and corporate financing

This study examines biodiversity concern, quantified through text analysis of corporate annual reports. If such mentions are merely "cheap talk" without concrete environmental actions, their policy relevance is diminished. Key questions remain: Do firms expressing greater biodiversity concern actually improve environmental performance? Furthermore, does a stronger focus on biodiversity enhance access to financing?

We first analyze the LCCP policy's impact on corporate ESG scores in Table 4, columns (1) and (2). Using the overall ESG score and environmental subscore from Huazheng ESG as dependent variables, we determine that the policy does not significantly affect ESG scores of firms with zero biodiversity concern. However, the significantly positive interaction term between LCCP and biodiversity concern indicates that firms with a stronger biodiversity focus achieve better environmental performance under the policy. We next

[3] The only difference is that before LCCP implementation, the CSDID estimator does not use any specific year as the baseline. Instead, the estimator compares the two consecutive years before the policy's introduction, resulting in one less year compared with the TWFE approach.

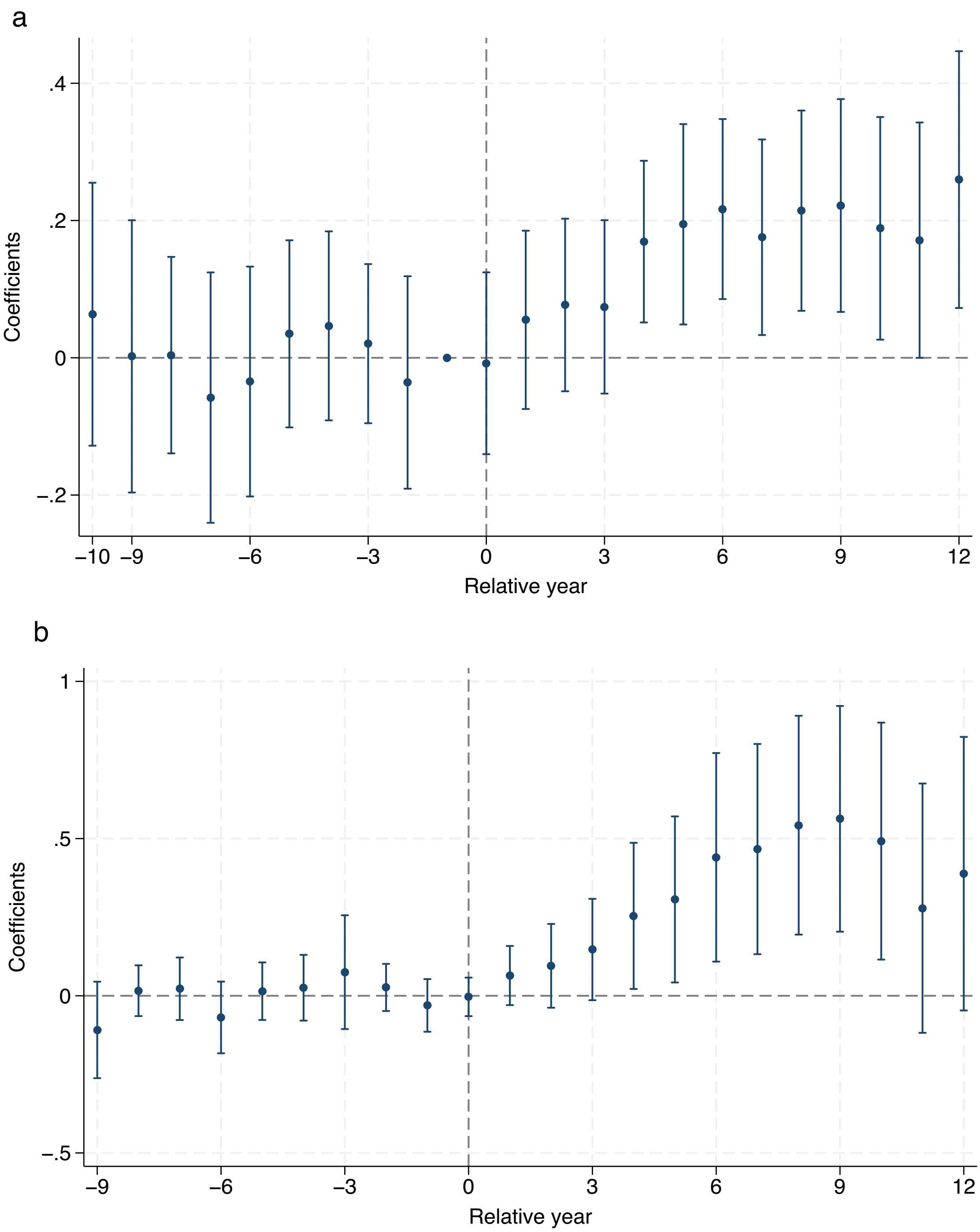

Fig. 2. Parallel trend test.
Note: This figure illustrates the dynamic effects before and after LCCP policy implementation. Panel (a) presents the TWFE estimators, and Panel (b) shows the CSDID estimators, both with 95% confidence intervals. The estimations include all control variables defined in Eq. (1), with standard errors clustered at the city-year level.

examine whether the policy influences corporate financing capacity, particularly for firms that prioritize biodiversity concerns. We estimate firms' financing capacity using the proportion of long-term loans and the ratio of bank loans to total assets as dependent variables. The results in columns (3) and (4) of Table 4 indicate that the policy's impact on financing capacity is more pronounced for firms with greater biodiversity concern.

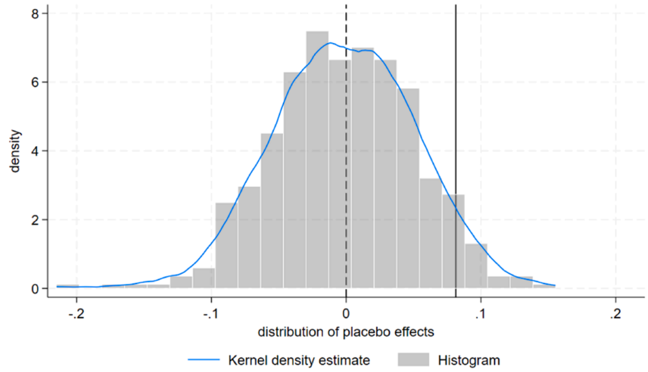

Fig. 3. Mixed placebo test.
Notes: This figure presents the mixed placebo test, randomly assigning treatment timings and units 500 times while preserving the cohort structure to generate the distribution of placebo estimators for $LCCP_{c,t}$.

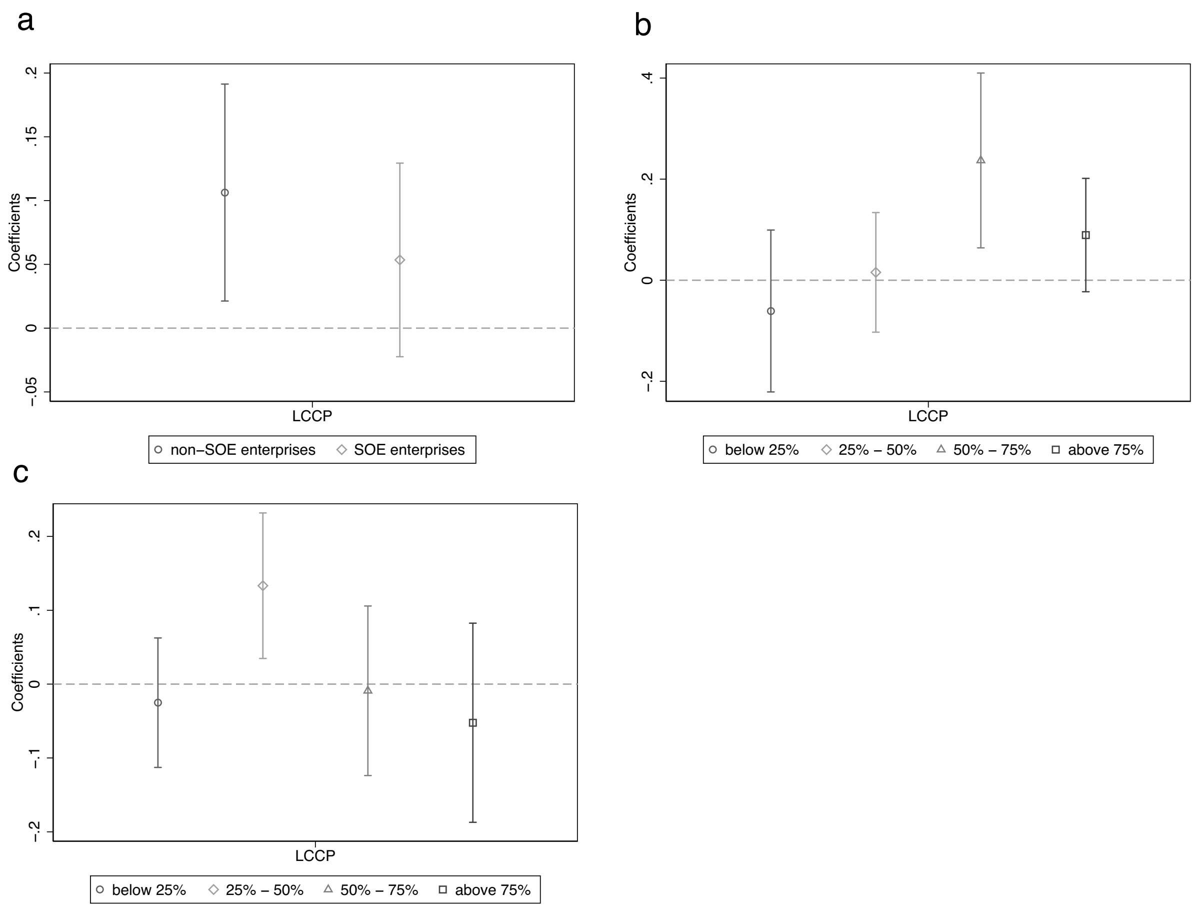

Fig. 4. Heterogeneous effects.
Note: This figure illustrates the heterogeneous effects of the LCCP policy, presenting TWFE estimators and their 95 % confidence intervals. The estimations include all control variables defined in Eq. (1), with standard errors clustered at the city-year level. The effects of the LCCP policy are estimated separately based on state ownership, Whited-Wu Index (2006) percentiles (25th, 50th, and 75th) and firm size percentiles (25th, 50th, and 75th) and are presented in Panels (a)–(c), respectively.

Table 4
Environmental performance and corporate financing.

Dep. Var.	ESG score (1)	ESG-E score (2)	Long-term loan ratio (3)	Bank Lev. (4)
LCCP	0.034	0.007	0.034***	0.002
	(0.027)	(0.026)	(0.009)	(0.012)
LCCP × Biodiversity concern	0.010**	0.019***	0.003**	0.002**
	(0.005)	(0.007)	(0.002)	(0.001)
Firm controls	✓	✓	✓	✓
City controls	✓	✓	✓	✓
Firm FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
#Obs	21,124	21,124	14,122	15,686
#Clusters	2837	2837	2783	2883
Adjusted R^2	0.494	0.534	0.400	0.212

Note: This table presents the results from the OLS regressions examining the impact of the LCCP policy and its interaction with biodiversity concern on environmental performance and corporate financing. Standard errors clustered at the city-year level are in parentheses. *, **, and *** denote significance at 10 %, 5 %, and 1 % levels, respectively.

4. Conclusion

This study demonstrates that low-carbon policies can increase firms' concern for biodiversity, and this concern is primarily driven by financing needs. Firms with a stronger focus on biodiversity are better positioned to respond to low-carbon policies, improve environmental performance, and enhance financing opportunities. However, such research remains in its early stages. Due to data limitations, we are unable to assess whether biodiversity concern translates into tangible biodiversity conservation, indicating avenues for future research.

Although low-carbon policies were not initially designed to address biodiversity, they have effectively increased manufacturing firms' attention to this issue. This raises an important question: Could policies explicitly targeting corporate biodiversity concerns more effectively incentivize firms to prioritize biodiversity? Currently, many ESG rating agencies in China do not include biodiversity in their evaluation criteria and related policies are notably absent. Governments should consider integrating biodiversity into environmental evaluations and policy frameworks, while financial institutions could support firms prioritizing biodiversity by offering favorable loan terms or reduced financing costs.

Author statement

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CRediT authorship contribution statement

Cong Nie: Writing – review & editing, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Chen Zhang:** Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization.

Appendix A

Table A1, Table A2

Table A.1
Variable definitions.

Variable	Description
Biodiversity concern	Frequency of biodiversity-related terms per 10,000 words in the annual reports.
LCCP	Dummy variable indicating the adoption of the Low-Carbon City Pilot policy.
Size	Logarithm of total assets.
Lev	Ratio of total debt to total assets.
ROA	Return on assets is defined as net profits over total assets.
Cash	Cash-to-assets ratio.

(*continued on next page*)

Table A.1 (*continued*)

Variable	Description
SOE	Dummy variable indicating a state-owned enterprise.
Female	Proportion of female directors on the board.
Indep.	Proportion of independent directors on the board.
lnBoard	Logarithm of the number of board directors.
Top1	Largest shareholder's ownership.
lnGDPpc	Logarithm of the city's per capita gross domestic product (GDP).
Ind.Share	Secondary industry share of GDP.
lnPop	Logarithm of the city's population.

Table A.2
Robustness tests.

	Poisson regression			OLS regression		
	(1)	(2)	(3)	(4)	(5)	(6)
Low-Carbon City Pilot	0.221***	0.193***	0.147**	0.055**	0.064**	0.054**
	(0.067)	(0.061)	(0.064)	(0.026)	(0.026)	(0.028)
Firm controls		✓	✓		✓	✓
City controls			✓			✓
Firm FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Subindustry (2-digit)-year FE				✓	✓	✓
#Obs	23,189	23,012	23,001	23,252	23,075	23,064
#Clusters	3197	3189	3178	3197	3189	3178
Pseudo (Adjusted) R^2	0.523	0.527	0.528	0.838	0.839	0.839

Note: This table presents a fixed effects (FE) Poisson model to accommodate the count-based dependent variable in columns (1)–(3). Columns (4)–(6) incorporate subindustry-year FE to account for variations in biodiversity concern across manufacturing subindustries while preserving TWFE estimators. Standard errors clustered at the city-year level are in parentheses. *, **, and *** denote significance at 10%, 5%, and 1% levels, respectively.

Data availability

Data will be made available on request.

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