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Firm-Level Nature Dependence and Green Innovation

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Abstract

Firms both influence natural systems and depend on the ecosystem services that support their ongoing production and operations. A higher degree of such dependence may strengthen firms' motivation to pursue green technologies aimed at conserving resources, limiting pollution, and mitigating nature-related operational exposure. Drawing on a panel of Chinese A-share firms observed during 2010–2023, we examine how firm-level nature dependence relates to corporate green innovation. The empirical evidence indicates that firms with stronger dependence on nature exhibit greater green innovation activity. This finding remains stable when the key variables are measured differently and when an alternative sample period is considered. A policy shock analysis based on China's Water Resource Tax Reform provides complementary evidence. Further analysis indicates that environmental investment accounts for part of the link between nature dependence and green innovation. Moreover, stronger local environmental regulation amplifies this relationship. Tests across different firm groups, together with formal interaction tests, show a stronger association among state-owned enterprises and firms in heavily polluting industries. The study therefore adds to prior research on corporate reliance on nature by demonstrating that reliance on ecosystem services can stimulate firms to undertake green technological adjustments.

Keywords: nature dependence; green innovation; environmental investment; environmental regulation

1. Introduction

Biodiversity decline and ecosystem degradation increasingly affect corporate operations. Corporate activities can impose pressures on natural systems through emissions, extraction of resources, and changes in land use, while firms simultaneously depend on those systems to sustain their production and operations. This dependence arises because production processes require diverse ecosystem functions, ranging from water availability and waste assimilation to climate and soil regulation, pollination, and natural-hazard protection. When these services deteriorate, firms may face higher production costs, greater operational uncertainty, and stronger environmental compliance pressure. Therefore, understanding how firms respond to their dependence on nature has become an important issue in sustainability and corporate finance research.

Recent research has increasingly examined firms' economic reliance on ecosystem services. Using information from the ENCORE framework together with firms' business-segment revenues, Garel et al. [1] develop a firm-level measure of nature dependence. This indicator captures the extent to which the composition of a firm's activities exposes it to dependence on ecosystem services. The subsequent literature can generally be divided

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into two research streams. One stream considers the consequences arising from stronger corporate dependence on nature. For instance, Garel et al. [1] associate higher NatureDep with greater downside risk and a higher incidence of nature-related events. Hoang and Vu [2] link nature dependence to supply chain risk, while Lee et al. [3] show that firms with higher nature dependence have higher carbon emissions. Wu and Chao [4] further report that greater dependence on nature is associated with weaker access to bank credit. A second stream focuses on the conditions that may help firms decrease their dependence on natural systems. Gan et al. [5] find that digital transformation is accompanied by a reduction in corporate nature dependence. Li and Huang [6] show that robot adoption reduces firm-level nature dependence through source-control green innovation and pollution reduction. Cai [7] and Liao et al. [8] further show that green investors and managerial climate risk perception can reduce corporate nature dependence.

Although this emerging literature has advanced our understanding of corporate nature dependence, an important question remains underexplored: does nature dependence itself motivate firms to engage in green innovation? This question matters because nature dependence is not only a passive exposure to ecosystem service disruption. It may also create pressure for firms to adjust production processes, reduce resource use, and control pollution. Green innovation provides a direct technological response to such pressure. By developing green technologies, firms can improve resource efficiency, reduce emissions, and lower their reliance on fragile ecosystem services.

This study examines whether firms that depend more heavily on nature exhibit higher levels of green innovation. Drawing on the natural-resource-based view, we argue that firms with higher nature dependence face stronger environmental constraints and therefore have greater incentives to build green capabilities. Green innovation is one way for firms to transform these constraints into technological responses. We further propose that environmental investment serves as a mediating channel. Nature-dependent firms need to allocate resources to environmental protection, cleaner production, and pollution control before nature-related pressure can be converted into green technological output. We also argue that environmental regulation intensity strengthens this relationship. When local governments place greater emphasis on environmental governance, firms with high nature dependence face stronger external institutional pressure, increasing their incentives for green innovation.

The empirical analysis is conducted using panel observations of Chinese A-share listed companies covering the period from 2010 to 2023. China provides a suitable setting because many listed firms operate in industries that rely heavily on ecosystem services, while environmental governance and green technological upgrading have become increasingly important during the sample period. We measure green innovation by the natural logarithm of one plus the number of green invention patent applications. Firm-level nature dependence is captured using NatureDep scores derived from ENCORE dependence assessments and the revenue composition of firms' business segments. The empirical strategy combines firm and year fixed effects with a series of robustness analyses, while China's Water Resource Tax Reform is further employed to obtain complementary evidence from a policy shock.

The estimates reveal a positive association between NatureDep and green innovation. This conclusion is preserved when alternative measures are used and when the sample window is changed. The policy shock analysis based on China's Water Resource Tax Reform provides complementary evidence. Firms with greater ex ante nature dependence exhibit a stronger increase in green innovation after the reform, and the dynamic analysis shows no clear evidence of differential pre-reform trends. Further mechanism analysis indicates that part of the association between nature dependence and green innovation

operates through environmental investment. The moderation results further indicate that stronger environmental regulation amplifies this positive association. Additional subgroup analyses, together with formal tests based on interaction terms, indicate that this relationship is more pronounced for state-owned enterprises and companies operating in heavily polluting industries.

This study makes three contributions. First, it introduces a response-based perspective into the growing literature on firm-level nature dependence. Existing studies mainly examine nature dependence as a source of corporate risk or as an outcome shaped by external factors. Using firm-level NatureDep scores, Garel et al. [1] demonstrate that dependence on ecosystem services is related to firms' exposure to physical nature-related risks. Hoang and Vu [2] associate greater nature dependence with supply chain risk, whereas Lee et al. [3] document higher carbon emissions among more nature-dependent firms. Wu and Chao [4] further find that stronger firm-level nature dependence corresponds to lower access to bank credit. Recent studies also examine how digital transformation, robot adoption, green investors, and managerial climate risk perception reduce firms' reliance on ecosystem services [5–8]. Our study adds a different perspective by demonstrating that greater dependence on nature may itself trigger green technological responses by firms.

Second, the study contributes to green innovation research by treating nature dependence as a resource constraint originating from the input side of production. Existing studies often explain green innovation through environmental regulation, pollution pressure, stakeholder demands, and firm resources. Many of these explanations focus on how firms respond to the environmental impacts of their activities. We focus instead on how firms respond to their reliance on ecosystem services. This distinction reveals a different motivation for green innovation. Accordingly, firms may undertake green innovation not merely to mitigate their environmental impacts, but also to ease production constraints arising from their dependence on natural resources. Third, the study connects the natural-resource-based view with institutional theory to explain firms' responses to nature dependence. Hart [9] argues that environmental capabilities related to pollution prevention, product stewardship, and sustainable development can become sources of competitive advantage. Our results indicate that dependence on nature can encourage firms to develop these capabilities through greater environmental investment and green technological activity. In addition, the moderating role of environmental regulation intensity is consistent with institutional theory, which argues that external institutional pressure shapes organizational behavior [10]. This study therefore shows how internal nature-related pressure and external institutional pressure jointly shape firms' green innovation decisions.

2. Theoretical Background and Hypothesis Development

2.1. Firm-Level Nature Dependence

Firms do not operate independently from the natural environment. A wide range of ecosystem functions support corporate production, including the provision of water, maintenance of water and soil quality, climate regulation, waste processing, pollination, and mitigation of natural hazards. These services are often treated as background conditions for production, but they can become important sources of business risk when ecosystems deteriorate. A firm with high nature dependence is therefore more exposed to disruptions in the natural systems that support its operations.

Nature dependence differs from conventional environmental indicators. Carbon emissions and pollution describe how firms affect the natural environment. Nature dependence describes how firms rely on the natural environment. From this perspective, it represents a production constraint arising from firms' reliance on natural inputs and ecological func-

tions. Such reliance may involve water availability, soil conditions, climate regulation, and various other services supplied by ecosystems. This dependence is different from pollution externalities generated during or after production. Nature dependence therefore captures a distinct relationship between firms and the natural environment. Garel et al. [1] construct a company-level NatureDep measure by linking ENCORE dependence assessments with firms' business-segment revenue data. ENCORE identifies how different economic activities depend on ecosystem services. Garel et al. [1] aggregate these dependency ratings to the firm level by using the revenue composition of each firm's business segments. The resulting NatureDep value indicates how extensively the firm's portfolio of business activities relies on ecosystem services. A higher score means that the firm's operations are more reliant on ecosystem services and are therefore more vulnerable to the deterioration or disruption of those services.

Recent research has increasingly explored the corporate consequences associated with dependence on natural systems. One branch of this literature focuses on the risks arising from such dependence. Garel et al. [1] find that firms with stronger NatureDep are more exposed to downside risk and experience more nature-related incidents. Hoang and Vu [2] further show that firms with greater nature dependence face higher supply chain risk because their input costs become more volatile and their inventory buffers become weaker. Another stream links nature dependence to environmental outcomes. Lee et al. [3] find that both the level and intensity of carbon emissions are greater for firms that depend more heavily on nature. These findings indicate that corporate nature dependence has implications beyond ecology and can materially affect firms' risk exposure and environmental outcomes.

Another line of research considers the mechanisms through which firms can become less dependent on ecosystem services. Gan et al. [5] show that digital transformation can lower corporate nature dependence partly by fostering substantive green innovation and raising green total factor productivity. Li and Huang [6] find that robot adoption is associated with weaker firm-level nature dependence through stronger source-control green innovation and lower pollution. Cai [7] shows that the effect of green institutional investors on reducing corporate nature dependence operates through enhanced managerial environmental awareness, improved green governance, and greater environmental investment. Liao et al. [8] further demonstrate that managerial perceptions of climate risk are linked to lower nature dependence through green strategic orientation and business diversification. These studies indicate that corporate nature dependence is not fixed. It can be changed by technology, governance, managerial cognition, and strategic adjustment.

Although this emerging literature has advanced our understanding of nature dependence, most existing studies focus on either the consequences of nature dependence or the factors that reduce it. Less attention has been devoted to whether greater reliance on nature can itself induce firms to undertake green innovation. This question is important because nature dependence may create pressure for firms to reduce resource use, control pollution, and improve production processes. Green innovation is a direct way for firms to respond to this pressure. Therefore, this study extends the literature by investigating whether differences in firms' dependence on natural systems are associated with their green innovation activities.

2.2. Nature Dependence and Green Innovation

As discussed above, firm-level nature dependence indicates how strongly a firm's production and continued operations are tied to ecosystem services. The next question is whether such dependence affects firms' green innovation decisions. We argue that heavier dependence on nature creates greater incentives for firms to pursue green innovation,

as green technologies offer ways to conserve resources, mitigate pollution, and decrease reliance on vulnerable ecosystem services.

The natural-resource-based view offers the theoretical basis for explaining this relationship. Hart [9] broadens the resource-based view by considering how constraints arising from the natural environment influence corporate strategy and the sources of competitive advantage. From this perspective, firms can build valuable capabilities by addressing environmental constraints through preventing pollution, managing products responsibly, and pursuing sustainable development. Green innovation can therefore be understood as an important environmental capability. Khanra et al. [11] also suggest that green innovation represents a strategic resource available to firms because it helps firms balance resource consumption with resource preservation while supporting sustainable development.

This logic is especially relevant to nature dependence. Nature-dependent firms rely on ecosystem services as inputs or operating conditions. A shortage or deterioration of these services can directly disrupt production. End-of-pipe treatment cannot fully address this type of constraint because it mainly deals with pollution after it has been generated. Firms therefore have stronger incentives to change the production process itself. They can reduce resource use, improve resource efficiency, recycle materials, and adopt cleaner production technologies. These source control responses can reduce firms' reliance on ecosystem services. Green innovation therefore becomes an important way to respond to nature dependence.

This theoretical argument is particularly applicable to firms whose operations depend heavily on nature. For these firms, ecosystem services are not distant environmental issues. They are direct production conditions. Water supply, waste treatment, climate regulation, soil quality, and protection from natural hazards can affect production costs, operational stability, and environmental compliance. When firms rely more heavily on these ecosystem services, deterioration or disruption of natural systems may increase their exposure to resource constraints and operating uncertainty. As a result, nature-dependent firms have stronger incentives to develop capabilities that reduce their reliance on these services.

Green innovation provides a direct technological response to this pressure. Process-oriented green innovation can lower firms' consumption of water and energy, raise the efficiency of material use, and reduce pollution during production. Product-oriented green innovation, in turn, allows firms to develop products with lower material requirements, less pollution generation, and reduced environmental burdens. These innovations help firms reduce their dependence on ecosystem services and improve their ability to operate under environmental constraints.

Existing research on nature dependence also provides evidence that green innovation can help firms become less reliant on natural systems. Gan et al. [5] show that the decline in nature dependence associated with digital transformation is partly attributable to substantive green technologies, especially source-control innovation. Li and Huang [6] similarly find that robot adoption is linked to lower NatureDep through enhanced source-control innovation and reductions in pollution intensity. These findings imply that green innovation is an important technological pathway through which firms can reduce dependence on ecosystem services. Building on this logic, firms that are more dependent on nature should have stronger incentives to pursue green innovation.

Taken together, greater dependence on nature is expected to be associated with more active corporate green innovation. Firms with higher nature dependence face stronger environmental constraints and greater exposure to ecosystem service disruption. To manage these constraints, they are more likely to develop green technologies that reduce resource use, lower pollution, and improve production efficiency. Based on the above reasoning, we formulate the following hypothesis:

H1. *Firm-level nature dependence is positively associated with green innovation.*

2.3. Environmental Investment Channel

Environmental investment may help explain why greater firm-level nature dependence is associated with stronger green innovation. Although nature dependence can create pressure for firms to reduce resource use and pollution, this pressure does not automatically become green innovation. Green innovation requires financial resources, equipment upgrading, production process adjustment, and technical learning. Environmental investment can therefore serve as an intermediate mechanism that converts nature-related pressure into green technological outcomes.

From the natural-resource-based view, firms may develop environmental capabilities as a response to ecological constraints. Hart [9] emphasizes pollution prevention, product stewardship, and sustainable development as key strategic approaches through which firms can build competitive advantage from their relationship with the natural environment. These strategies require firms to commit resources to cleaner production, pollution control, resource efficiency, and environmental management. Khanra et al. [11] further show that green innovation constitutes a strategic resource for firms because it helps firms address the tension between resource consumption and resource preservation. From this perspective, environmental investment provides the resource base for firms to develop green innovation capabilities.

Greater firm-level nature dependence may encourage firms to allocate more resources to environmental investment. Garel et al. [1] characterize NatureDep as capturing both corporate reliance on ecosystem services and exposure to physical risks arising from nature. Firms with higher nature dependence rely more heavily on ecosystem services such as water supply, waste treatment, climate regulation, soil quality, and protection from natural hazards. When these services become less stable or more costly, firms may face higher production costs, greater pollution control pressure, and stronger operational uncertainty. In response to these risks, firms may expand spending on environmental facilities and technologies, including energy-saving equipment, wastewater and waste-gas treatment systems, cleaner production processes, and resource-recycling facilities.

Environmental investment can then promote green innovation. Such investment is not merely a compliance cost. It can provide firms with equipment, technical conditions, and organizational routines needed for green technology development. For example, investment in wastewater treatment or energy-saving facilities can help firms accumulate technical knowledge about cleaner production. Investment in pollution-control equipment can also create opportunities for process redesign and source-control innovation. These activities can support green patent applications by improving firms' ability to develop technologies that reduce resource use, lower emissions, and improve production efficiency.

Recent studies on nature dependence also support the role of green technological responses. Gan et al. [5] find that the decline in nature dependence associated with digital transformation is partly driven by substantive green innovation and gains in green total factor productivity. Li and Huang [6] show that robot adoption is linked to lower firm-level nature dependence through stronger source-control green innovation and reduced pollution. Cai [7] further reports that green investors can lessen corporate nature dependence by improving environmental awareness, strengthening governance, and increasing environmental investment. These findings suggest that environmental investment and green technological improvement are important ways for firms to reduce their reliance on ecosystem services.

Taken together, greater dependence on nature is expected to induce firms to devote more resources to environmental investment in response to resource constraints, pollution

pressure, and nature-related operational risks. Environmental investment then provides the material and technical foundation for green innovation. Therefore, firm-level nature dependence can promote green innovation through environmental investment. Based on the above reasoning, we formulate the following hypothesis:

H2. *Firm-level nature dependence promotes green innovation by increasing environmental investment.*

2.4. Moderating Role of Environmental Regulation Intensity

Environmental regulation intensity is treated as a moderating variable in this study. Unlike environmental investment, which represents an internal corporate response, environmental regulation is an external institutional intervention imposed by governments. It does not represent an internal transmission mechanism through which nature dependence affects green innovation. Instead, environmental regulation alters the external conditions and incentives confronting firms, thereby influencing how strongly nature dependence is associated with green innovation. Although greater reliance on nature can expose firms to more pronounced pressures to conserve resources, curb pollution, and address nature-related risks, they may not always respond actively. Some firms may postpone green innovation because it requires financial investment, technical adjustment, and organizational change. Environmental regulation can therefore serve as an important boundary condition that determines how strongly nature dependence is translated into green innovation. Institutional theory provides a useful explanation for this moderating effect. DiMaggio and Powell [10] argue that organizations are influenced by institutional pressures in their external environment. These pressures can shape organizational behavior by requiring firms to conform to rules, norms, and social expectations as a means of maintaining organizational legitimacy. Within the environmental domain, institutional pressure can come from government regulation, public policy priorities, and social expectations about environmental protection. Prior studies on environmental innovation also show that institutional pressures can affect firms' incentives to adopt eco-innovation and environmental management practices [12,13]. Recent evidence also emphasizes that external circumstances and contextual features can condition the effects of organizational and innovation-related factors [14,15].

Environmental regulation intensity captures the degree of environmental governance pressure exerted by local governments. When environmental protection, pollution abatement, energy conservation, and ecological governance receive greater attention from local authorities, firms face stronger external pressure to improve their environmental behavior. In such an institutional environment, firms are less able to ignore nature-related risks or delay green transformation. Environmental regulation therefore strengthens the link between nature dependence and firms' green innovation decisions.

For highly nature-dependent firms, stricter environmental regulation increases the consequences of delaying action. Such firms depend more intensively on ecosystem services, including water supply, waste treatment, climate regulation, and protection from natural hazards. When environmental regulation is weak, firms may treat nature dependence as a long-term risk and delay technological adjustment. However, when environmental regulation is strong, nature-dependent firms face both internal operational pressure and external institutional pressure. This combination increases their incentives to develop green technologies that reduce resource use, lower pollution, and improve production efficiency.

Accordingly, stronger environmental regulation is expected to amplify the positive association between firm-level nature dependence and green innovation. Under more stringent environmental regulation, firms that depend more heavily on nature are more inclined

to respond to ecosystem-service constraints through green technological development. Based on this reasoning, we formulate the following hypothesis:

H3. *The positive relationship between firm-level nature dependence and green innovation is stronger when environmental regulation intensity is higher.*

3. Data and Methodology

3.1. Sample and Data Sources

Our empirical sample consists of firms listed on China's A-share market over the 2010–2023 period. This setting allows us to investigate the association between firm-level nature dependence and green innovation. Many firms operate in business activities that rely substantially on ecosystem services, while environmental governance and green technological upgrading have received increasing policy attention in China during the sample period.

The sample selection starts with all firms listed on China's A-share market during 2010–2023. Financial companies are first excluded given the substantial differences in their business models and financial structures relative to nonfinancial firms. We then remove ST and ST companies because their unusual financial conditions and specific regulatory status may influence corporate behavior. Firm-year observations with missing data for the baseline model are also eliminated. Following these screening steps, the final sample comprises 18,039 firm-year observations.

3.2. Variable Definitions

3.2.1. Dependent Variable

The dependent variable is green innovation (GI). Consistent with prior green innovation studies, GI is defined as the natural logarithm of one plus the annual number of green invention patent applications submitted by a firm. We rely on invention patents because they generally involve greater technological novelty and more stringent inventive requirements, making them more appropriate for capturing substantive green technological innovation than utility-model patents. Higher GI values therefore represent stronger green innovation performance. As a robustness measure, we alternatively use the number of green invention patents granted to the firm (GIGrant).

3.2.2. Independent Variable

Firm-level nature dependence (NatureDep) serves as the main independent variable. Following Garel et al. [1], we construct NatureDep by weighting the ENCORE-based ecosystem-service dependence of each business segment by its share of firm revenue, with cultural services excluded. This indicator represents how strongly the activities undertaken by a firm depend on ecosystem functions, including water provision, waste treatment, climate regulation, soil quality, and natural-hazard protection. Greater values of NatureDep correspond to heavier reliance on ecosystem services and stronger exposure to operational constraints arising from nature. For robustness, we also employ NatureDepHigh, which counts the ecosystem services for which a firm's revenue-weighted dependence reaches a score of 4 or above.

Although the ENCORE dependency ratings are fixed at the economic activity level, firm-level NatureDep can change over time. This is because the measure uses annual business segment revenues as weights. Changes in the revenue share of different business activities therefore change a firm's NatureDep score. In practice, such changes can arise from different growth rates across existing business segments, entry into or exit from business activities, diversification, mergers and acquisitions, divestitures, or changes in

the firm's core business. Thus, the time variation in NatureDep reflects changes in the composition and relative importance of firms' business activities.

3.2.3. Mediating Variable

Environmental investment (EnvInv) serves as the mediating variable and is calculated by dividing a firm's environmental investment by its total assets. It includes environmental expenditures recognized either as capitalized assets or current expenses, covering wastewater and waste-gas treatment, energy-saving equipment, desulfurization and dust-control activities, waste and waste-heat treatment, tail-gas management, environmental fees, and vegetation restoration. This variable captures the extent to which firms allocate resources to environmental protection and green production improvement.

3.2.4. Moderating Variable

Environmental regulation intensity (ER) is employed as the moderating variable. We quantify ER using the share of environmental-protection-related terms appearing in municipal government work reports. Larger ER values indicate that local governments devote greater attention to environmental governance, pollution abatement, energy conservation, emission reduction, and ecological protection. Accordingly, ER captures the degree of external institutional pressure imposed on firms by their local regulatory environment.

3.2.5. Control Variables

The baseline specification includes controls for firm size, liquidity and cash flow, investment and capital structure, corporate governance, firm age, growth opportunities, and innovation input. MV denotes market value expressed in RMB 100 million. CashFlow captures operating cash flow, whereas Quick measures short-term liquidity. Capex refers to capital expenditure, while CAP represents capital intensity. Board is measured by board size, and Indep denotes the share of independent directors. Dual takes the value of one when the chairman also serves as CEO, and zero otherwise. Female measures the proportion of female directors. FirmAge is the number of years since the firm was established, and TobinQ proxies for growth opportunities. R&D_Intensity equals R&D expenditure scaled by total assets and multiplied by 100, and is included to control for firms' general innovation input. The construction of all variables can be seen in Table 1.

3.3. Model Specification

To examine the relationship between firm-level nature dependence and green innovation, we estimate the following baseline model:

$$GI_{i,t} = \alpha + \beta_1 \, NatureDep_{i,t} + Controls + Firm + Year + \varepsilon_{i,t} \quad (1)$$

where $GI_{i,t}$ represents green innovation of firm (i) in year (t). $NatureDep_{i,t}$ is firm-level nature dependence. *Controls* denotes a set of firm-level control variables, including market value, cash flow, quick ratio, capital expenditure, capital intensity, board size, independent director ratio, CEO duality, female director ratio, firm age, Tobin's Q, and R&D intensity. *Firm* represents firm fixed effects, and *Year* represents year fixed effects. $\varepsilon_{i,t}$ is the error term.

Table 1. Variable definitions.

Variable	Definition	Source
Dependent variable and its alternatives		
GI	Natural logarithm of one plus the number of green invention patent applications.	CSMAR; authors' calculation
GIGrant	Number of granted green invention patents.	CSMAR; authors' calculation
Independent variable and its alternatives		
Nature dependence	Revenue-weighted dependence of a firm's business segments on ecosystem services identified in the ENCORE framework, excluding cultural services	Garel et al. [1]
High nature dependence	Number of revenue-weighted dependence scores on ecosystem services greater than or equal to 4	Garel et al. [1]
Control variables		
MV	Market value in the current year, scaled by RMB 100 million.	CSMAR
CashFlow	Cash flow ratio.	CSMAR
Quick	Quick ratio.	CSMAR
Capex	Capital expenditure.	CSMAR
CAP	Capital intensity.	CSMAR
Board	Board size.	CSMAR
Indep	Ratio of independent directors on the board.	CSMAR
Dual	Indicator variable equal to one if the chairman and CEO are held by the same person, and zero otherwise.	CSMAR
Female	Ratio of female directors on the board.	CSMAR
FirmAge	Number of years since firm establishment.	CSMAR
TobinQ	Tobin's Q.	CSMAR
R&D Intensity	(R&D/Assets) $\times 100$.	CSMAR

Table 1. *Cont.*

Variable	Definition	Source
Channel variable		
Environmental investment	Environmental investment (EnvInv) is measured as the ratio of environmental investment to total assets. Environmental investment includes capitalized and expensed expenditures related to environmental protection, such as wastewater treatment, waste gas treatment, energy-saving facilities, desulfurization, dust removal, waste treatment, waste heat recovery, tail gas treatment, sewage fees, environmental protection fees, and vegetation restoration fees.	CSMAR; authors' calculation
Moderating Variable		
Environmental regulation intensity	Environmental regulation intensity (ER) is measured by the proportion of words related to environmental protection in city-level government work reports. A higher value indicates stronger environmental regulation intensity.	Government work reports; authors' calculation

The panel nature of the data is accommodated through firm and year fixed effects. Firm fixed effects absorb unchanging firm-specific attributes, including business models, industry positioning, organizational culture, and long-term technological capabilities, that may jointly relate to nature dependence and green innovation. Year fixed effects capture shocks common to all firms, including macroeconomic conditions, nationwide environmental policies, and shifts in incentives for green innovation. Together, these fixed effects allow the estimation to focus on how within-firm changes in nature dependence are associated with within-firm changes in green innovation over time. The key parameter is β1. A positive and statistically significant β1 would be consistent with higher nature dependence being associated with greater green innovation. More specifically, the within-firm variation in NatureDep comes from changes in the revenue composition of business activities with different levels of ecosystem service dependence. The firm fixed effects model therefore uses changes in firms' business composition rather than changes in the underlying ENCORE dependency ratings for identification. Because changes in business composition can themselves result from endogenous strategic choices, the fixed-effects estimates should be interpreted as within-firm associations after accounting for time-invariant firm characteristics, rather than as estimates identified exclusively by exogenous variation in NatureDep. The policy-shock analysis in Section 4.4 is used to provide complementary evidence.

We acknowledge that changes in business composition may themselves reflect endogenous strategic decisions. Therefore, the firm fixed-effects estimates should be interpreted as within-firm associations that control for time-invariant firm characteristics, rather than as relying solely on exogenous changes in NatureDep. We complement these estimates with the policy-shock analysis reported in Section 4.4.

4. Empirical Results

4.1. Descriptive Statistics and Correlation Analysis

Table 2 presents descriptive statistics for the key variables. The mean value of GI is 0.696, with a standard deviation of 0.999, showing substantial dispersion in firms' green innovation activities. NatureDep has a mean of 2.913 and a standard deviation of 0.379, indicating meaningful variation in firms' reliance on ecosystem services.

Panel B of Table 2 further decomposes the variation in NatureDep. Its between-firm standard deviation is 0.366, compared with a within-firm standard deviation of 0.138. Thus, although variation in NatureDep is primarily cross-sectional, the measure also changes within firms over time. Such within-firm movements reflect shifts in the revenue composition of business activities characterized by different levels of ecosystem-service dependence.

Table 3 reports the pairwise correlations among the main variables. GI and NatureDep have a correlation coefficient of 0.053, which is significant at the 1% level and indicates an initial positive association between them. Nevertheless, this simple correlation does not control for firm-specific factors, year-specific shocks, or other variables that may affect green innovation. The regression analysis that follows therefore examines this association after these influences are taken into account.

4.2. Baseline Results

Table 4 contains the baseline estimates. Column (1) includes firm and year fixed effects without introducing the firm-level controls. NatureDep is estimated at 0.0848 and is significant at the 1% level. This estimate points to a positive association between firms' dependence on nature and their green innovation activities.

Table 2. Descriptive statistics.

Panel A. Descriptive Statistics					
Variable	**Count**	**Mean**	**Sd**	**Min**	**Max**
GI	18,039	0.696	0.999	0.000	6.636
NatureDep	18,039	2.913	0.379	1.705	3.991
MV	18,039	259.182	1005.142	4.689	29,899.068
CashFlow	18,039	0.043	0.069	−0.556	0.839
Quick	18,039	1.541	1.537	0.040	36.246
Capex	18,039	0.046	0.049	−0.502	0.603
CAP	18,039	2.441	3.469	0.088	289.885
Board	18,039	2.120	0.200	1.386	2.890
Indep	18,039	0.376	0.055	0.167	0.800
Dual	18,039	0.294	0.455	0.000	1.000
Female	18,039	0.195	0.113	0.000	0.722
FirmAge	18,039	2.982	0.316	1.386	4.304
TobinQ	18,039	1.980	1.391	0.625	26.818
R&D_Intensity	18,039	2.205	2.178	0.000	73.780
Panel B. Variance Decomposition of NatureDep					
Variable	**Count**	**Mean**	**Overall SD**	**Between SD**	**Within SD**
NatureDep	18,039	2.913	0.379	0.366	0.138

Table 3. Correlation analysis.

	GI	**NatureDep**	**MV**	**CashFlow**	**Quick**	**Capex**	**CAP**	**Board**	**Indep**	**Dual**	**Female**	**FirmAge**	**TobinQ**	**R&D**
GI	1.000													
NatureDep	0.053 ***	1.000												
MV	0.355 ***	0.066 ***	1.000											
CashFlow	0.033 ***	0.101 ***	0.048 ***	1.000										
Quick	−0.106 ***	−0.064 ***	−0.086 ***	0.033 ***	1.000									
Capex	0.014 *	0.134 ***	−0.001	0.164 ***	−0.010	1.000								
CAP	−0.007	−0.052 ***	−0.001	−0.105 ***	0.062 ***	0.022 ***	1.000							
Board	0.100 ***	0.048 ***	0.085 ***	0.052 ***	−0.099 ***	−0.030 ***	−0.012 *	1.000						
Indep	0.032 ***	−0.017 **	0.091 ***	−0.015 **	0.014 *	0.006	0.006	−0.545 ***	1.000					
Dual	−0.080 ***	−0.010	−0.062 ***	−0.022 ***	0.093 ***	0.085 ***	−0.001	−0.185 ***	0.110 ***	1.000				
Female	−0.150 ***	−0.073 ***	−0.123 ***	−0.002	0.095 ***	−0.002	0.040 ***	−0.189 ***	0.065 ***	0.148 ***	1.000			
FirmAge	0.062 ***	0.011	−0.005	0.034 ***	−0.116 ***	−0.155 ***	0.030 ***	0.070 ***	−0.042 ***	−0.091 ***	0.064 ***	1.000		
TobinQ	−0.136 ***	−0.028 ***	−0.054 ***	0.034 ***	0.159 ***	0.015 **	−0.006	−0.111 ***	0.052 ***	0.075 ***	0.098 ***	−0.062 ***	1.000	
R&D	0.101 ***	−0.063 ***	−0.073 ***	0.039 ***	0.130 ***	0.051 ***	−0.122 ***	−0.085 ***	0.037 ***	0.104 ***	0.044 ***	−0.058 ***	0.225 ***	1.000

This table reports Pearson correlation coefficients. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

Table 4. Baseline model.

	Bivariate Regression	**Added Controls**
	(1) GI	(2) GI
NatureDep	0.0848 *** (2.78)	0.0941 *** (3.15)
MV		0.0004 *** (23.92)
CashFlow		−0.0642 (−0.81)
Quick		0.0047 (1.07)
Capex		0.7092 *** (5.73)
CAP		−0.0073 *** (−4.80)
Board		0.1228 ** (2.32)
Indep		0.3853 ** (2.44)
Dual		0.0114 (0.74)
Female		−0.1905 ** (−2.50)
FirmAge		0.0190 (0.19)
TobinQ		−0.0253 *** (−5.10)
R&D_Intensity		0.0256 *** (5.80)
_cons	0.4484 *** (5.04)	−0.1284 (−0.36)
Firm	YES	YES
Year	YES	YES
N	18,039	18,039
r2_a	0.6818	0.6957

T-statistics in parentheses. ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

In Column (2), the complete set of firm-level controls is incorporated. NatureDep remains positive, with an estimated coefficient of 0.0941, which is statistically significant (t = 3.15). The result indicates that the positive link between nature dependence and green innovation continues to hold after controlling for firm size, cash flow, liquidity, capital expenditure, capital intensity, board characteristics, firm age, growth opportunities, and R&D intensity.

Overall, the baseline evidence is consistent with H1. Firms that depend more strongly on nature exhibit greater green innovation activity. This pattern accords with the argument that heavier reliance on ecosystem services exposes firms to more pronounced environmental constraints and therefore has greater incentives to develop green technologies that reduce resource use, control pollution, and improve production efficiency.

4.3. Robustness Checks

The robustness analyses are presented in Table 5. First, GIGrant, defined as the count of green invention patents that receive approval, is used in place of the original dependent variable. NatureDep is estimated at 0.8074 and reaches statistical significance at the 1% level.

The estimate indicates that the documented positive association with nature dependence persists when green innovation is represented by granted green invention patents.

Table 5. Robustness checks.

	Replacing Dependent Variable	**Replacing Independent Variable**	**Changing Sample Period**
	(1)	(2)	(3)
	GIGrant	GI	GI
NatureDep	0.8074 ***		0.0942 ***
	(3.56)		(2.87)
NatureDepHigh		0.0139 ***	
		(3.37)	
MV	0.0051 ***	0.0004 ***	0.0004 ***
	(44.12)	(23.32)	(18.68)
CashFlow	−0.6955	−0.0178	−0.0172
	(−1.28)	(−0.23)	(−0.19)
Quick	0.0191	0.0046	0.0019
	(0.60)	(1.08)	(0.38)
Capex	−1.0223	0.6625 ***	0.5416 ***
	(−1.18)	(5.45)	(3.86)
CAP	−0.0093	−0.0033 **	−0.0056 ***
	(−0.85)	(−2.16)	(−3.54)
Board	−0.4426	0.1065 **	0.1487 **
	(−1.19)	(2.04)	(2.45)
Indep	−0.8654	0.3431 **	0.4742 ***
	(−0.79)	(2.21)	(2.64)
Dual	0.1542	0.0078	0.0188
	(1.42)	(0.51)	(1.04)
Female	0.4399	−0.1729 **	−0.2244 **
	(0.83)	(−2.31)	(−2.45)
FirmAge	1.8789 ***	0.0408	0.0383
	(2.65)	(0.40)	(0.32)
TobinQ	−0.1363 ***	−0.0239 ***	−0.0191 ***
	(−3.95)	(−4.91)	(−3.48)
R&D_Intensity	0.0396	0.0266 ***	0.0210 ***
	(1.30)	(6.15)	(4.27)
_cons	−6.6840 ***	0.0302	−0.2970
	(−2.67)	(0.09)	(−0.72)
Firm	YES	YES	YES
Year	YES	YES	YES
N	16,156	17,647	14,030
r2_a	0.6608	0.7197	0.7513

T-statistics in parentheses. ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

Second, NatureDepHigh is employed as an alternative measure of the independent variable. It counts the ecosystem services whose revenue-weighted dependence score for a firm reaches 4 or higher. NatureDepHigh has a coefficient of 0.0139, which is statistically significant at the 1% level. The estimate indicates that firms dependent on a larger number of highly relevant ecosystem services display greater green innovation activity.

Third, we alter the estimation period to assess whether the main finding depends on the particular sample window. NatureDep continues to show a positive and statistically significant coefficient of 0.0942, with a t-statistic of 2.87. The persistence of this result indicates that the documented association between firm-level nature dependence and green innovation is not specific to the original sample period.

Taken together, the evidence in Table 5 supports the stability of the baseline result. The positive association between firm-level nature dependence and green innovation persists across an alternative outcome measure, a different proxy for nature dependence, and a modified sample window.

We additionally perform placebo tests to assess whether random variation could account for the baseline finding. The baseline model is repeatedly re-estimated after randomizing the relevant assignments, generating distributions of pseudo coefficients and associated *p*-values. Figures 1 and 2 display these two distributions, respectively. The pseudo coefficients cluster near zero, whereas the coefficient obtained from the actual data is positioned away from the central mass of the placebo distribution. This contrast indicates that random assignment is unlikely to explain the observed positive association between firm-level nature dependence and green innovation. The placebo evidence thus reinforces the stability of the baseline finding.

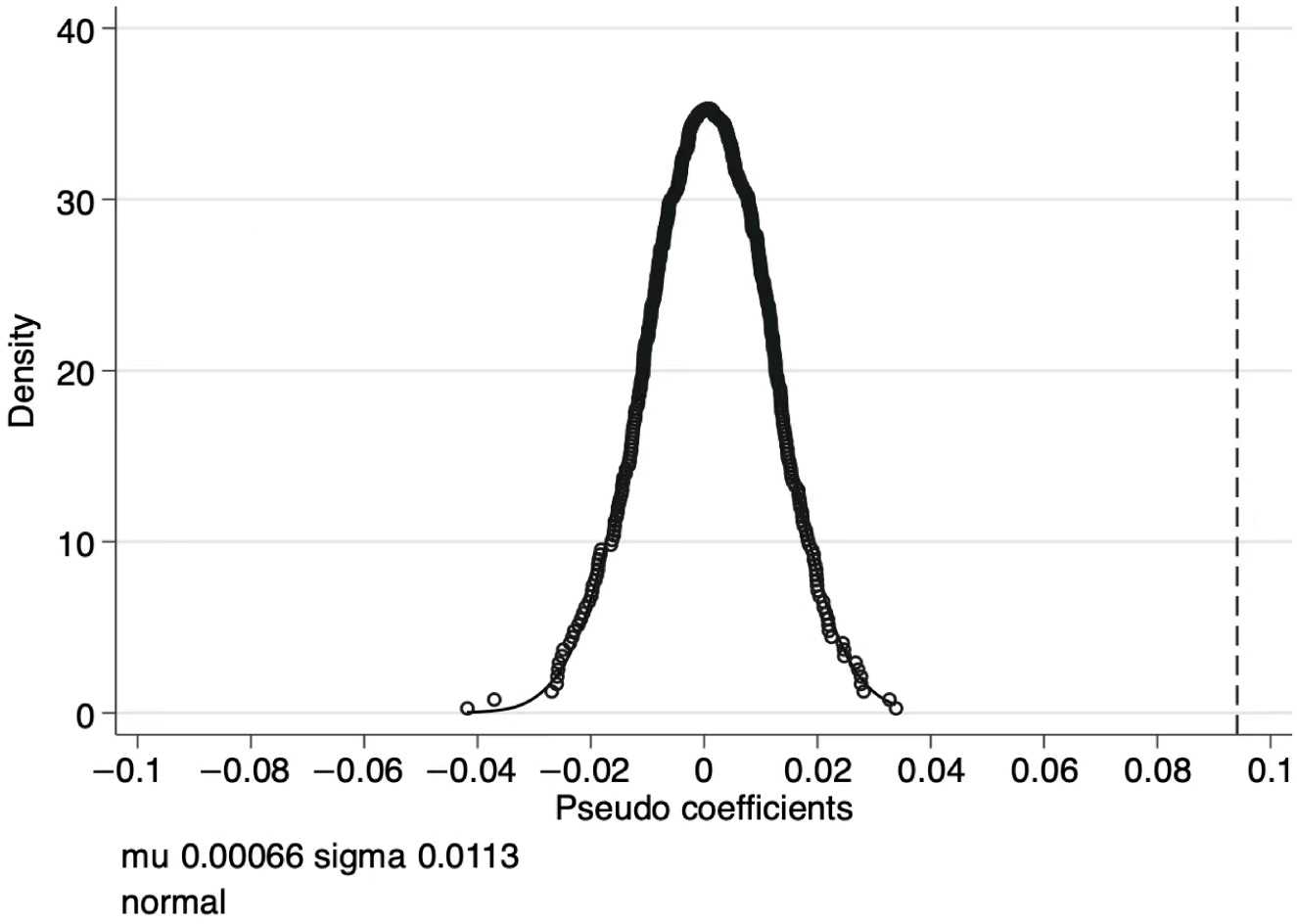


Figure 1. Placebo test: Kernel density of placebo coefficients.

4.4. Policy Shock Analysis

Potential endogeneity may still affect the baseline estimates. To provide complementary policy-shock evidence, we exploit China's Water Resource Tax Reform. The reform increased the economic and regulatory pressure associated with water use in pilot regions. Although NatureDep captures firms' dependence on a broad range of ecosystem services, water-related ecosystem services are particularly relevant to its economic implications. Garel et al. [1], who develop the NatureDep measure, show that the association between nature dependence and downside risk stems mainly from high dependence on water-related ecosystem services. Water therefore represents an economically important dimension of

firm-level nature dependence. Accordingly, the reform provides a relevant setting for examining whether firms with greater ex ante nature dependence exhibit stronger green innovation responses when an important ecosystem-service input becomes more costly and salient.

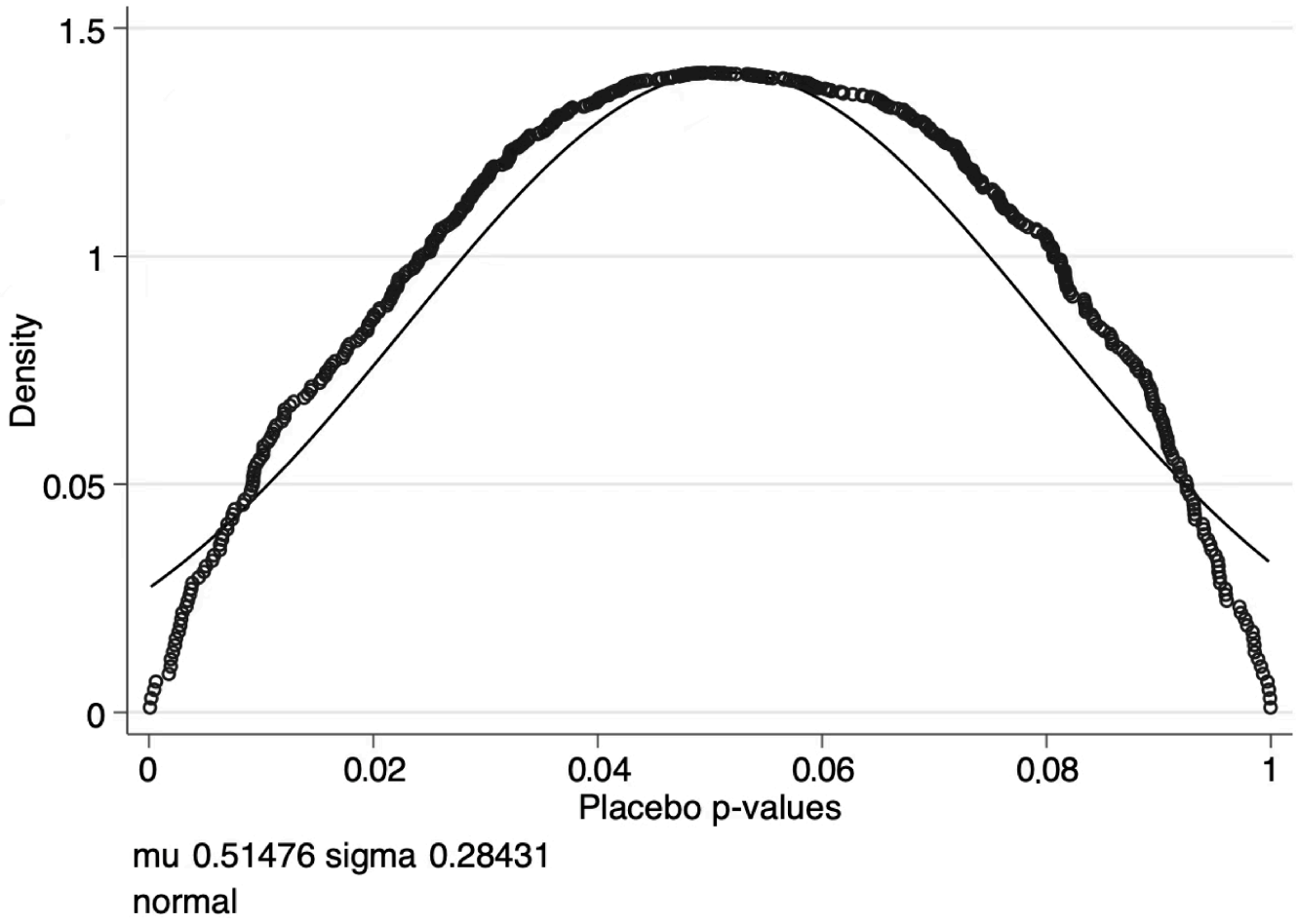


Figure 2. Placebo test: Kernel density of placebo *p*-values.

The reform was first implemented in Hebei and was subsequently extended to several additional pilot regions. We classify firms located in reform pilot regions as the treatment group and those located elsewhere as the control group. To reduce the influence of partial-year implementation, the post period begins from the first full calendar year after the reform. Ex ante nature dependence is constructed from each firm's average pre-reform NatureDep and is subsequently standardized. Our focal variable is the interaction of this standardized ex ante NatureDep measure with the policy indicator.

Table 6 presents the estimation results. The interaction between the policy indicator and ex ante nature dependence has a coefficient of 0.0505 and is statistically significant at the 1% level. This estimate indicates that the post-reform increase in green innovation is greater among firms with higher ex ante nature dependence. By contrast, the coefficient on the policy indicator itself is statistically insignificant. The evidence therefore indicates that firms' innovation responses to the reform vary with their pre-existing dependence on ecosystem services. Firms with greater nature dependence respond more strongly when external resource constraints become more salient.

Table 6. Policy Shock Analysis: Water Resource Tax Reform and Ex Ante Nature Dependence.

	(1)
	GI
DID	0.0278
	(1.17)
DID_PreNatureDep	0.0505 ***
	(2.72)
MV	0.0004 ***
	(21.45)
CashFlow	−0.0735
	(−0.76)
Quick	0.0015
	(0.29)
Capex	0.7331 ***
	(4.85)
CAP	−0.0068 ***
	(−4.13)
Board	0.1137 *
	(1.90)
Indep	0.3660 **
	(2.07)
Dual	0.0192
	(1.06)
Female	−0.2003 **
	(−2.24)
FirmAge	−0.0230
	(−0.20)
TobinQ	−0.0229 ***
	(−3.79)
R&D_Intensity	0.0244 ***
	(4.85)
_cons	0.3303
	(0.85)
Firm	YES
Year	YES
N	12,820
r2_a	0.7008

T-statistics in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

Importantly, we do not interpret the Water Resource Tax Reform as a shock to all dimensions of NatureDep. Rather, the reform represents a resource-specific policy shock to an economically important component of ecosystem-service dependence. The results therefore provide complementary evidence that firms with greater overall nature dependence respond more strongly when a salient natural-resource constraint is intensified.

Accordingly, this policy-shock analysis should be interpreted as complementary evidence from a water-specific resource constraint rather than as direct causal identification of the effect of overall NatureDep.

We next assess the dynamic response to the reform and test the parallel-trends condition. The year immediately preceding the reform serves as the omitted reference period, and the corresponding estimates are reported in Table 7 and Figure 3. The interaction terms for the pre-reform years are statistically insignificant, providing no clear indication that firms with different levels of ex ante nature dependence followed different trends before the policy change. After the reform, the interaction coefficients turn positive and statistically significant and remain so in later periods. This temporal pattern suggests that the stronger

green innovation response among firms with greater nature dependence appears only after the reform. Overall, the dynamic evidence is consistent with a positive association between firm-level nature dependence and green innovation.

Table 7. Dynamic Effects of the Water Resource Tax Reform by Ex Ante Nature Dependence.

	(1)
	GI
pre4_nd	−0.0152
	(−0.46)
pre3_nd	0.0344
	(0.92)
pre2_nd	−0.0230
	(−0.59)
current_nd	0.0790 **
	(2.01)
post1_nd	0.1650 ***
	(3.58)
post2_nd	0.1300 ***
	(2.79)
post3_nd	0.1354 ***
	(2.98)
post4_nd	0.1292 ***
	(3.32)
_cons	0.3729
	(0.96)
Controls	YES
Firm	YES
Year	YES
N	12,820
r2_a	0.7008

T-statistics in parentheses. ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

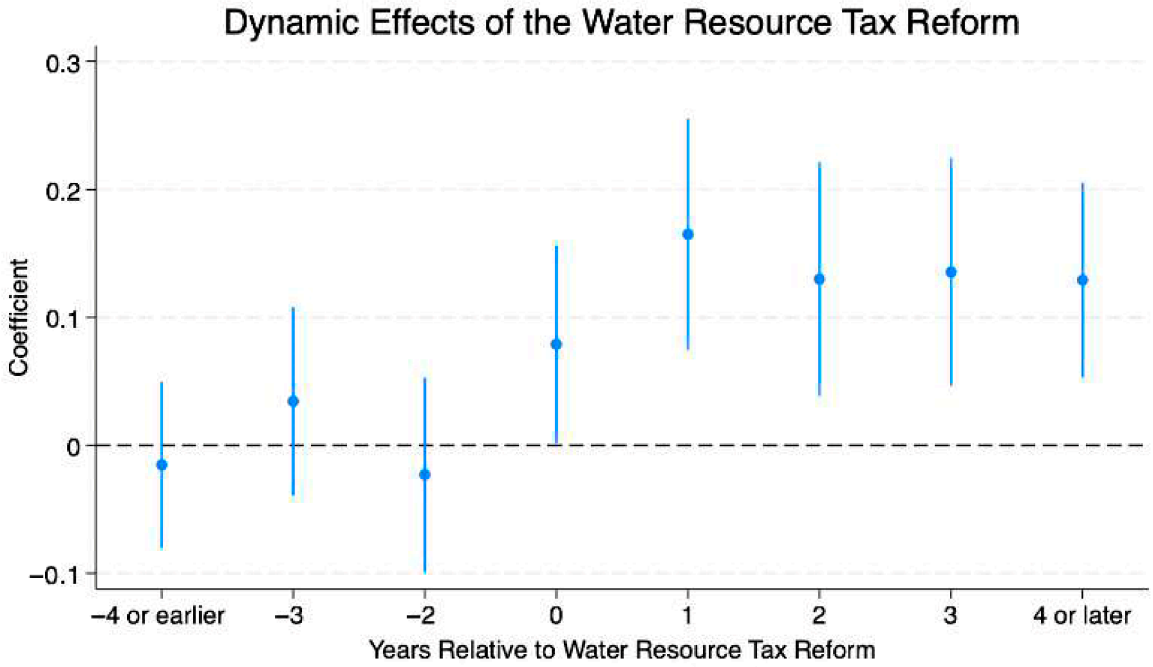


Figure 3. Parallel Trends and Dynamic Effects of the Water Resource Tax Reform.

4.5. Environmental Investment Channel

Table 8 presents the evidence on the environmental investment channel. Column (1) evaluates whether nature dependence is associated with firms' environmental investment. NatureDep has a coefficient of 0.1367 and is statistically significant at the 1% level. The estimate shows that environmental investment tends to be greater among firms with stronger nature dependence. This pattern accords with the argument that firms relying more heavily on nature encounter stronger resource constraints, pollution control pressure, and nature-related operational risks, which motivate them to allocate more resources to environmental protection and green production improvement.

Table 8. Environmental investment channel.

	(1)	(2)
	EnvInv	**GI**
NatureDep	0.1367 ***	
	(2.82)	
EnvInv		0.0183 ***
		(3.66)
MV	−0.0000	0.0004 ***
	(−0.08)	(23.90)
CashFlow	−0.1041	−0.0612
	(−0.81)	(−0.77)
Quick	−0.0152 **	0.0049
	(−2.13)	(1.11)
Capex	3.2358 ***	0.6511 ***
	(16.11)	(5.22)
CAP	−0.0003	−0.0073 ***
	(−0.12)	(−4.77)
Board	−0.0185	0.1248 **
	(−0.22)	(2.36)
Indep	−0.2198	0.3863 **
	(−0.86)	(2.45)
Dual	0.0446 *	0.0102
	(1.78)	(0.66)
Female	−0.0409	−0.1887 **
	(−0.33)	(−2.48)
FirmAge	−0.1547	0.0206
	(−0.93)	(0.20)
TobinQ	−0.0068	−0.0247 ***
	(−0.84)	(−4.98)
R&D_Intensity	−0.0099	0.0258 ***
	(−1.38)	(5.86)
_cons	0.3336	0.1326
	(0.58)	(0.38)
Firm	YES	YES
Year	YES	YES
N	18,039	18,039
r2_a	0.4623	0.6958
Sobel Test	0.0018 *** (z = 2.161)	
Goodman1	0.0018 *** (z = 2.109)	
Goodman2	0.0018 *** (z = 2.218)	

Table 8. *Cont.*

		(1)		(2)		
		EnvInv		**GI**		
Dependent Variable	Mediating Variable	Effect Type	Effect Size	Standard Error	95% Confidence Interval	
					Lower Bound	Upper Bound
GI	EnvInv	Indirect Effect	0.0018	0.0007	0.0003	0.0032
		Direct Effect	0.0691	0.0235	0.0229	0.1153

Bootstrap mediation test (5000 replications). T-statistics in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

Column (2) turns to the association between environmental investment and green innovation. EnvInv carries a coefficient of 0.0183 that is statistically significant at the 1% level. This estimate points to a positive association between environmental investment and green innovation. Environmental investment can provide firms with equipment, technical conditions, and organizational support for cleaner production, energy saving, pollution control, and process upgrading. These inputs help firms develop green technologies and increase green patent applications.

We further evaluate the mediation effect using 5000 bootstrap resamples. The estimated indirect effect is 0.0018, and its 95% bootstrap confidence interval is [0.0003, 0.0032]. Because this interval excludes zero, the indirect effect is statistically significant. The Sobel [16] and Goodman [17] tests yield the same conclusion. Nevertheless, the estimated indirect effect is small in magnitude. Environmental investment should therefore be viewed as a partial and relatively limited channel linking firm-level nature dependence to green innovation, rather than as the predominant mechanism.

Overall, the findings support H2. This evidence suggests that environmental investment constitutes a statistically significant but relatively modest mediating channel through which firms translate nature-related pressure into green technological responses.

As an additional check on the temporal sequence of the proposed channel, we re-estimate the model using green innovation in year t + 1 as the outcome variable. Table 9 shows that current environmental investment remains positively related to green innovation in the subsequent year, with a coefficient of 0.0170 and a t-statistic of 2.72. Thus, environmental investment is associated with both current and subsequent green innovation. This lagged specification provides further evidence that is consistent with the proposed temporal ordering of the mediating channel.

Table 9. Robustness Test of the Mediation Effect Using Green Innovation in t + 1.

	(1)	**(2)**
	EnvInv	**F.GI**
NatureDep	0.1367 ***	
	(2.82)	
EnvInv		0.0170 ***
		(2.72)
MV	−0.0000	0.0004 ***
	(−0.08)	(18.76)
CashFlow	−0.1041	−0.0674
	(−0.81)	(−0.70)
Quick	−0.0152 **	0.0122 **
	(−2.13)	(2.15)

Table 9. *Cont.*

	(1)	(2)
	EnvInv	**F.GI**
Capex	3.2358 ***	0.4772 ***
	(16.11)	(3.15)
CAP	−0.0003	0.0025
	(−0.12)	(1.41)
Board	−0.0185	0.1317 **
	(−0.22)	(2.09)
Indep	−0.2198	0.2654
	(−0.86)	(1.41)
Dual	0.0446 *	0.0288
	(1.78)	(1.53)
Female	−0.0409	−0.2837 ***
	(−0.33)	(−3.03)
FirmAge	−0.1547	0.0923
	(−0.93)	(0.73)
TobinQ	−0.0068	−0.0048
	(−0.84)	(−0.78)
RD_Intensity	−0.0099	0.0349 ***
	(−1.38)	(5.18)
_cons	0.3336	−0.0912
	(0.58)	(−0.22)
Firm	YES	YES
Year	YES	YES
N	18,039	13,346
r2_a	0.4623	0.7049

T-statistics in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

4.6. Moderating Effect of Environmental Regulation Intensity

Table 10 reports the analysis of the moderating role of environmental regulation intensity. The interaction term for firm-level nature dependence and environmental regulation intensity, ND_ER, is positive and statistically significant. The estimated value of ND_ER is 0.1689 (t = 2.64). These results suggest that greater environmental regulation intensity increases the strength of the positive association between nature dependence and green innovation.

Table 10. Moderation analysis: Environmental regulation intensity.

	(1)
	GI
NatureDep	−0.0633
	(−0.93)
ER	−0.4329 **
	(−2.30)
ND_ER	0.1689 ***
	(2.64)
MV	0.0004 ***
	(23.56)
CashFlow	−0.0615
	(−0.77)
Quick	0.0049
	(1.11)

Table 10. *Cont.*

	(1)
	GI
Capex	0.7234 ***
	(5.81)
CAP	−0.0072 ***
	(−4.73)
Board	0.1234 **
	(2.33)
Indep	0.3773 **
	(2.39)
Dual	0.0078
	(0.50)
Female	−0.1856 **
	(−2.43)
FirmAge	0.0192
	(0.19)
TobinQ	−0.0261 ***
	(−5.22)
R&D_Intensity	0.0258 ***
	(5.83)
_cons	0.2748
	(0.69)
Firm	YES
Year	YES
N	17,911
r2_a	0.7412

T-statistics in parentheses. ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

This evidence is consistent with H3. Under more intensive environmental regulation, greater nature dependence is associated with stronger engagement in green innovation. A possible explanation is that stronger environmental regulation increases the external institutional pressure faced by firms. For firms that already rely heavily on ecosystem services, this external pressure makes nature-related operational risks more salient and increases the cost of delaying green transformation. As a result, these firms have stronger incentives to develop green technologies that reduce resource use, control pollution, and improve production efficiency.

4.7. Heterogeneity Analysis

Ownership-based differences are examined in Panel A of Table 11. For state-owned enterprises, the estimated coefficient on NatureDep is 0.1983 and significant at the 1% level, whereas the corresponding estimate for non-state-owned enterprises is 0.0815 and significant at the 5% level. To determine whether this difference is statistically meaningful, we estimate an additional specification using the full sample and include the interaction term between NatureDep and SOE. The estimated ND_SOE coefficient is 0.1156, with a t-statistic of 2.05, and is significant at the 5% level. This interaction evidence indicates that the association between nature dependence and green innovation is significantly stronger for state-owned firms.

Table 11. Heterogeneity Analysis and Interaction-Based Difference Tests.

Panel A. Heterogeneity by State Ownership			
	SOEs	**Non-SOEs**	**Between-Group Difference Test**
	(1)	**(2)**	**(3)**
	GI	**GI**	**GI**
NatureDep	0.1983 ***	0.0815 **	0.0820 **
	(2.88)	(2.37)	(2.51)
SOE			−0.2667 *
			(−1.65)
ND_SOE			0.1156 **
			(2.05)
MV	0.0003 ***	0.0005 ***	0.0003 ***
	(15.99)	(15.13)	(21.65)
CashFlow	−0.4342 ***	0.0590	−0.0828
	(−2.72)	(0.64)	(−1.06)
Quick	0.0194	−0.0009	0.0070
	(1.34)	(−0.18)	(1.59)
Capex	0.8436 ***	0.5258 ***	0.6954 ***
	(2.89)	(3.87)	(5.70)
CAP	−0.0175 ***	−0.0056 ***	−0.0031 **
	(−3.56)	(−3.56)	(−1.99)
Board	0.1242	0.0963	0.0975 *
	(1.26)	(1.47)	(1.86)
Indep	0.6035 **	0.2006	0.3783 **
	(2.27)	(0.99)	(2.44)
Dual	0.0279	0.0044	0.0020
	(0.79)	(0.25)	(0.13)
Female	−0.2551	−0.1418	−0.1909 **
	(−1.55)	(−1.63)	(−2.54)
FirmAge	0.0184	0.3452 ***	0.0617
	(0.10)	(2.70)	(0.61)
TobinQ	−0.0339 ***	−0.0275 ***	−0.0233 ***
	(−2.78)	(−5.01)	(−4.78)
R&D_Intensity	0.0326 ***	0.0233 ***	0.0270 ***
	(2.61)	(5.00)	(5.83)
_cons	−0.2216	−1.0299 **	−0.2208
	(−0.32)	(−2.36)	(−0.63)
Firm	YES	YES	YES
Year	YES	YES	YES
N	5582	12,076	17,658
r2_a	0.6608	0.7197	0.6794
Panel B. Heterogeneity by Pollution Intensity			
	Heavily Polluting Industries	**Non-Heavily Polluting Industries**	**Between-Group Difference Test**
	(1)	**(2)**	**(3)**
	GI	**GI**	**GI**
NatureDep	0.2326 ***	0.0730 **	0.0813 **
	(3.15)	(2.18)	(2.50)
Pollute			−0.5933 ***
			(−2.76)
ND_Pollute			0.1906 ***
			(2.65)

Table 11. *Cont.*

Panel B. Heterogeneity by Pollution Intensity			
	Heavily Polluting Industries	**Non-Heavily Polluting Industries**	**Between-Group Difference Test**
	(1) **GI**	**(2)** **GI**	**(3)** **GI**
MV	0.0006 ***	0.0004 ***	0.0004 ***
	(11.75)	(21.71)	(24.66)
CashFlow	−0.1261	−0.0420	−0.0429
	(−0.75)	(−0.46)	(−0.54)
Quick	0.0268 ***	−0.0008	0.0041
	(2.68)	(−0.17)	(0.94)
Capex	0.7795 ***	0.6719 ***	0.6933 ***
	(3.35)	(4.56)	(5.63)
CAP	−0.0203 **	−0.0068 ***	−0.0072 ***
	(−2.15)	(−4.44)	(−4.71)
Board	0.0537	0.1246 **	0.1334 **
	(0.50)	(2.03)	(2.53)
Indep	0.7183 **	0.2680	0.4199 ***
	(2.21)	(1.48)	(2.67)
Dual	−0.0144	0.0192	0.0087
	(−0.44)	(1.10)	(0.57)
Female	−0.2055	−0.1086	−0.1924 **
	(−1.21)	(−1.26)	(−2.54)
FirmAge	−0.3658	0.0097	0.0066
	(−1.52)	(0.09)	(0.06)
TobinQ	−0.0205	−0.0238 ***	−0.0259 ***
	(−1.53)	(−4.45)	(−5.27)
R&D_Intensity	0.0533 ***	0.0213 ***	0.0260 ***
	(3.68)	(4.60)	(5.93)
_cons	0.4666	0.0094	−0.0957
	(0.56)	(0.02)	(−0.27)
Firm	YES	YES	YES
Year	YES	YES	YES
N	4262	13,628	17,890
r2_a	0.6409	0.7521	0.6866

T-statistics in parentheses. * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$. Source(s): Author's computation.

One possible explanation is that state-owned firms bear greater policy responsibilities and environmental governance expectations. When their dependence on nature is relatively high, these firms are more inclined to address nature-related operating risks and environmental constraints through green innovation. In addition, state-owned enterprises usually have better access to financial and policy resources, which may help them transform nature-related pressure into green technological activities.

Panel B of Table 11 examines whether the relationship differs with pollution intensity. Among heavily polluting firms, NatureDep is estimated at 0.2326 and is significant at the 1% level. For firms outside this group, the corresponding coefficient is 0.0730 and significant at the 5% level. We then test the between-group difference directly in the full sample by adding the interaction between NatureDep and Pollute. The coefficient on ND_Pollute is 0.1906, with a t-statistic of 2.65, and is significant at the 1% level. The interaction estimate confirms that the positive association between nature dependence and green innovation is significantly stronger among heavily polluting firms.

This result is consistent with the theoretical logic of this study. Firms operating in heavily polluting industries generally encounter greater resource consumption, pollution-control pressure, and environmental compliance requirements. When high nature dependence is also present, the pressure from ecosystem service reliance and pollution control becomes more salient. Therefore, they have stronger incentives to develop green technologies that reduce resource use, control emissions, and improve production efficiency.

Taken together, the subgroup estimates and formal interaction tests indicate that the association between firm-level nature dependence and green innovation varies systematically across firms. This positive association is significantly more pronounced in state-owned enterprises and heavily polluting firms, where policy obligations, environmental pressures, and resource constraints tend to be more substantial.

5. Discussion

The empirical evidence reveals a consistent link between firms' reliance on nature and their green innovation activities. This association survives alternative variable definitions and changes in the estimation period. Evidence from the Water Resource Tax Reform further shows that firms with greater pre-reform nature dependence respond more strongly when water-related resource pressures intensify, while the dynamic estimates do not indicate systematic differences before the reform. The mechanism analysis suggests that environmental investment explains a limited but statistically significant portion of this association. The strength of the relationship also rises with environmental regulation intensity. In addition, the interaction-based heterogeneity tests show that the association is stronger for state-owned enterprises and firms operating in heavily polluting industries.

These findings add to the developing research on firm-level nature dependence. Existing studies have largely considered nature dependence as a source of corporate risk or as an outcome shaped by technology, governance, and managerial cognition. For example, Garel et al. [1] show that firm-level nature dependence captures exposure to physical nature-related risks. Hoang and Vu [2] link nature dependence to supply chain risk, while Lee et al. [3] associate it with carbon emissions. Other studies show that digital transformation, robot adoption, green investors, and managerial climate risk perception can reduce firms' reliance on ecosystem services [5–8]. Our study moves beyond these perspectives by showing that nature dependence can itself stimulate firms' green innovation responses rather than serving only as a source of risk or an object of reduction. Our findings complement these studies by examining the relationship from a different direction. Previous research indicates that green technologies, digital transformation, and environmental investment can lower firms' dependence on nature, whereas our evidence suggests that nature dependence itself may create incentives for firms to pursue green technological responses. Taken together with prior research, these findings point to a potential feedback relationship in which nature dependence may create pressure for green adjustment, while green technological development may subsequently help firms reduce their reliance on ecosystem services.

The findings also extend the natural-resource-based view. Hart [9] links competitive advantage to the development of environmental capabilities involving pollution prevention, product stewardship, and sustainable development. Our evidence indicates that nature dependence can generate pressure for firms to develop these green capabilities. Green innovation becomes a practical way for firms to reduce resource use, control pollution, and manage ecosystem service constraints. This interpretation is also in line with the resource-based perspective on green innovation, under which green innovation is viewed as a strategic organizational resource that can contribute to sustainable development [11]. In addition, our evidence on environmental regulation is compatible with institutional theory,

which emphasizes the role of external institutional pressures in shaping organizational behavior [10].

These results have broader practical implications for firms, investors, financial institutions, and policymakers. For firms, nature dependence should be treated as a strategic operational risk rather than a distant environmental issue. Managers need to identify which production activities rely heavily on ecosystem services and then direct environmental investment toward cleaner production, pollution control, resource recycling, and green technology upgrading. For investors, firm-level nature dependence provides useful information for evaluating future transition pressure and nature-related risk exposure. Firms with high nature dependence may face greater pressure to adjust their production processes, but they may also have stronger incentives to develop green technologies. Investors can therefore use nature dependence as an additional signal when assessing firms' long-term sustainability and innovation potential. For financial institutions, nature dependence can improve the assessment of environmental risk in credit allocation and investment decisions. Banks and other lenders may pay attention not only to firms' current pollution levels, but also to their dependence on ecosystem services and their ability to reduce such dependence through green innovation. For policymakers, the findings suggest that environmental regulation can help transform nature-related pressure into green technological responses. Policies that improve environmental governance, support environmental investment, and encourage green patenting may help firms reduce their reliance on fragile ecosystem services while promoting high-quality green development.

6. Conclusions

Using panel data on Chinese A-share firms from 2010 to 2023, we document that greater firm-level dependence on nature is associated with more green innovation. This pattern is unchanged when alternative variable constructions and different sample windows are considered. Evidence from the Water Resource Tax Reform is also consistent with the baseline finding: firms that were more dependent on nature before the reform display larger subsequent innovation responses when water-related resource constraints become more stringent. Environmental investment accounts for a statistically significant but modest part of this association, whereas stronger environmental regulation increases its magnitude. Interaction tests further indicate that the association is more pronounced for state-owned enterprises and heavily polluting firms. Taken together, the results suggest that reliance on ecosystem services may motivate firms to undertake green technological adjustment rather than functioning solely as a source of operational exposure.

The findings also carry theoretical and practical implications. From a theoretical perspective, our evidence extends the natural-resource-based view by indicating that reliance on ecosystem services can operate as an input-side resource constraint that encourages green technological responses. It also highlights environmental regulation as an external institutional condition that strengthens this response. Practically, firms with high nature dependence should identify critical ecosystem service dependencies and direct environmental investment toward resource efficiency and cleaner production. Policymakers can further encourage such responses by strengthening environmental governance and supporting firms' green technological upgrading.

This study has several limitations. First, although NatureDep offers a firm-level indicator of reliance on ecosystem services, its construction combines business-segment revenues with ecosystem-service dependence ratings. Therefore, it may not fully capture firm-specific production processes, local ecological conditions, or supplier-level dependence on nature. Second, green innovation is proxied by applications for green invention patents. Although patent-based measures capture formal technological outputs, they may not fully

reflect non-patented green process improvements, informal technological upgrading, or internal environmental management practices. Third, the empirical evidence is drawn from Chinese listed companies. The institutional setting, environmental regulation system, and green innovation incentives in China may differ from those in other economies. Therefore, the external validity of the findings needs further examination.

Several avenues remain for future research. First, more granular information on production processes, supply chains, and geographic exposure could be used to develop finer firm-level measures of nature dependence. Second, researchers can examine whether nature dependence affects other corporate decisions, such as environmental disclosure, supply chain restructuring, financing structure, risk management, and long-term firm value. Third, cross-country analyses could investigate whether the association between nature dependence and green innovation differs across institutional, regulatory, and market settings. Finally, future studies may explore how different types of green innovation, such as source-control innovation, end-of-pipe innovation, and low-carbon innovation, respond differently to nature dependence.

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