ISSN 2090-3359 (Print)
ISSN 2090-3367 (Online)

Advances in Decision Sciences

Volume 30
Issue 2
June 2026

亞洲大學 ASIA UNIVERSITY
SCIENTIFIC & BUSINESS WORLD

Published by Asia University, Taiwan and Scientific and Business World

Mitigating Corporate Biodiversity Risk through Green Finance: The Role of Green Development and Climate Risk in the USA

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Received: January 1, 2026; First Revision: June 14, 2026;

Last Revision: June 20, 2026; Accepted: June 25, 2026;

Published: July 1, 2026

Abstract

Purpose - This study examines whether green finance mitigates corporate biodiversity risk in the United States, focusing on the decision-making mechanisms underlying this relationship. It specifically evaluates the mediating role of corporate green development and the moderating effect of climate risk in shaping firms' responses to sustainability-oriented financial incentives.

Design/methodology/approach - Using a balanced panel of U.S. publicly listed firms from 2003 to 2025, corporate biodiversity risk is measured through BERT-based textual analysis of 10-K disclosures aligned with the Taskforce on Nature-related Financial Disclosures (TNFD) framework. Green finance is captured using a state-level Green Finance Development Index constructed via the Entropy Weight Method. The empirical strategy employs firm and year fixed effects, Propensity Score Matching (PSM), and a Difference-in-Differences (DID) approach to address endogeneity. Mediation analysis is applied to examine corporate green development as a transmission mechanism, while moderation analysis is used to assess whether climate risk strengthens the effect of green finance on corporate green development.

Findings - The results show that green finance significantly reduces corporate biodiversity risk ($p < 0.01$). Corporate green development, proxied by Green Total Factor Productivity (GTFP), serves as a significant mediating channel, indicating that financial incentives promote environmentally efficient practices. Climate risk strengthens this relationship, suggesting that firms in high-risk environments respond more strongly to green finance signals. The findings are robust across multiple specifications.

Originality/Value - This study is among the first to integrate green finance, climate risk, and biodiversity exposure within a unified decision-making framework at the firm level. Employing TNFD-aligned textual analysis and a mediation–moderation structure provides rare empirical evidence on how financial systems influence corporate responses to nature-related risks in a developed economy. The study contributes to *Advances in Decision Sciences* by offering evidence-based insights into how sustainability-oriented financial incentives shape corporate risk management, resource allocation, and strategic adaptation under environmental uncertainty, thereby enhancing decision-making in complex and evolving risk.

Keywords: GFTP; Sustainable Finance; Climate Risk; Corporate Green Development; Biodiversity Risk; U.S. listed corporations

JEL Classifications: G32, Q56, Q57, G38, F65, Q54

1 Introduction

Biodiversity loss has developed as a leading sustainable challenge of this century, as more than a million species of plants, fungi, and animals face extinction as a result of deforestation, industrialization, and unsustainable production (IPBES, 2019). A loss of biodiversity affects ecosystems as well as poses significant material risks to business operations, finance, and sustainable expansion in the future. Incorporating biodiversity into financial assessments has emerged as an area of sustainable finance that is in its pioneering phase (Karolyi & Tobin-de la Puente, 2023). The Kunming–Montreal Global Biodiversity Framework (GBF) emphasizes that bridging the biodiversity finance gap is imperative, which demands hundreds of billions of dollars annually, to enable living in harmony with nature by 2050 (Seidl et al., 2024).

Recently, the financial community has progressively recognized biodiversity damage as a substantial economic risk that has substantial consequences for economic valuation, economic market dynamics, and financial system stability. Giglio et al. (2023) constructed a biodiversity risk exposure index employing the United States widely accessible documents, which exhibited that the risk of biodiversity loss is already incorporated in stock pricing. Banks' increased loan spreads to exposure of biodiversity to companies, as well as widening corporate bond spreads during biodiversity-related shocks, respectively, have been observed by Li et al. (2025) and Cherief et al. (2025). Exposure of diversified companies to ecological risks is higher, as per Hasan et al. (2025). Improved crash risk likelihood for better biodiversity management has been concluded by Bassen et al. (2024). All in all, biodiversity loss, apart from being an environmental issue, is also a material financial risk, which financial markets cannot afford to neglect further.

Green finance has been recognized as a significant policy tool for leveraging finance towards environmentally responsible engagements. Green finance instruments, including green investment, insurance, bonds, and credit, leverage finance to support sustainability agendas. Empirical analyses suggest that green finance encourages green innovation (Lu et al., 2022; K. Xing et al., 2024), encourages green total factor productivity (Lee & Lee, 2022), and supports greenhouse gas emission reductions (L. Wang et al., 2024; Z. Wang et al., 2024). In addition, green finance encourages green transformation in terms of increased environmental responsibility, as presented by Hua et al. (2024). Nevertheless, although green finance is increasingly playing an important role in low-carbon transformation as well as waste reduction, the biodiversity-related risk management potential of green finance is inadequately studied, as in advanced countries, biodiversity disclosures remain a source of uncertainty (Nedopil, 2023). Nedopil (2023) underlines that biodiversity is yet to be increasingly recognized in financial systems in terms of financial undervaluation because of challenges in measurement, as well as diversified financial regulations.

Yet, despite the increasing body of research in this area, a significant research gap exists with regard to the impact of green finance on biodiversity risks faced by firms, especially in developed countries like the United States. Most of the existing research has focused on carbon emissions, climate risks, and overall environmental performance. However, the financial risks associated with biodiversity have been underresearched. In addition, the mediating and moderating effects of green finance have also been underresearched.

The green finance-biodiversity risk nexus is likely to function as follows: via an enhancement of corporate green development, which appears in sustainable manufacturing, resource optimization, and eco-minded innovation. There is support for financial motivation focusing upon green innovation, leading to observable positive environmental impacts (Hua et al., 2024; Lee & Lee, 2022; Uddin et al., 2025). This appears to highlight an intriguing but greatly overlooked dynamic, namely, that green finance can help minimize biodiversity risk by improving an organization's green development capabilities. From a theoretical perspective, this phenomenon can be explained by theories of environmental risk exposure and adaptive pressure. The former theory suggests that firms with high levels of ecological uncertainty tend to respond more proactively to sustainability-oriented financial incentives. Green finance helps to mitigate environmental risk by matching financial flows with environmentally friendly practices. Corporate green development serves as a transmission mechanism to convert financial inputs into ecological outputs. However, simultaneously, regional climate risk, which is defined by droughts, floods, heatwaves, and weather-related disasters, might also shape the intensity of this association. Climate-related disasters hasten biodiversity loss, but at the same time, they accelerate companies' pressures to build climate resilience (Guo et al., 2023; Privara et al., 2025; Ren et al., 2022). According to Kedward et al. (2023), climate, as well as biodiversity risk, are simultaneously treated as different risks and result in systematic error in financial exposure risk assessments. As a consequence, the effect of climate risk is expected to function as a moderating factor, which enhances the effectiveness of green finance, whereby the pressure for adaptation in biodiversity risk reduction will be intensified in firms located in vulnerable climatic areas.

The United States is a case of great interest for this study, as it is home to one of the biggest sustainable finance markets in the world (Ardia et al., 2023; Peng et al., 2022) at a time when it is also undergoing an extremely dynamic transition to nature-related risk disclosures, thanks to the Taskforce on Nature-related Financial Disclosures (TNFD). However, current scientific literature is characterized by an almost complete lack of studies which focus on state green finance systems as they influence corporate biodiversity risk, which makes it a gap in scientific literature that needs to be filled, as current literature is dominated by studies focusing either on carbon emissions, pollution, or climate transition challenges, to which biodiversity finance relationships have barely received any attention so far, as they relate to finance research involving biodiversity risks for corporations. At the same time, variations in U.S. state-level regulation, climate risk, and financial development provide an intrinsic natural laboratory for exploring green finance's differentially influencing biodiversity outcomes for corporations, as discussed in this study's hypothesis below.

Building on these gaps, this study investigates whether and how green finance mitigates corporate biodiversity risk among U.S.-listed firms from 2003 to 2025, while clearly assessing the climate risk's moderating role and corporate green development's mediating role. A comprehensive Green Finance Development Index (GFI) is constructed using the Entropy Weight Method, while corporate biodiversity risk (BR) is measured using advanced BERT-based textual analysis of 10-K filings guided by TNFD terminology. The analysis also investigates the role of the mediating corporate green development, proxied by GTFP (Green Total Factor Productivity), and the moderating effect of the regional climate risk using the NOAA-based indicators of the extreme weather incidents. The empirical analysis uses firm and year fixed effects, as well as Propensity Score Matching and a Difference-in-Differences approach, because of endogeneity.

The empirical findings indicate that green finance significantly reduces corporate biodiversity risk, with corporate green development serving as a mediating channel, while climate risk strengthens this relationship as a moderating factor.

This paper provides four important contributions to the existing literature. Firstly, the study provides novel firm-level evidence from a developed economy, addressing the limited empirical literature on biodiversity risk within financial systems. Secondly, it integrates a mediation–moderation framework, thereby advancing understanding of the transmission mechanisms through which green finance influences ecological outcomes. Thirdly, it presents a new measure of biodiversity risk through textual analysis by BERT with TNFD terminology to tackle the problem of quantifying the nature-related financial risks. Fourthly, the study has practical implications for policy makers, financial institutions, and corporate managers to develop effective sustainability-based financial strategies.

The remainder of this paper will be organized as follows. The next section will give a detailed analysis of the existing literature that will result in a hypothesis for the empirical analysis of this study. The second part of this paper explains the data sets, variables, and methods used in this research to answer the questions on green finance and biodiversity risks of companies. This is followed by a discussion on the findings of empirical analysis that will dwell on the direct, mediating, and moderating effects of green finance as shown by the findings of this study. Finally, this paper concludes by bringing together important results of this paper, pointing to limitations of this study, as well as ways to further explore this topic in future research.

2 Literature Review and Research Hypothesis

2.1 Literature Review

The increased pressing nature of environmental degradation, climate change, and biodiversity loss has greatly transformed the dialogue in the literature of finance and sustainability. This has been a growing trend over the last two decades, whereby scholarly interest has moved away, not only on more conventional environmental issues, like carbon emission and pollution management, but also to more ecological aspects, such as the preservation of biodiversity and the stability of ecosystems. This shift is a paradigm shift in sustainable finance, in which financial systems are no longer considered only as distributors of capital but as proactive tools that can be used to impact environmental performance and determine long-term ecological stability.

The extant literature can be classified into two strands, which are interconnected. The former strand is concerned with the development and efficiency of green finance in ensuring environmental sustainability. The second strand looks at how the risk of biodiversity becomes a risk that is financially material at the firm level. Merging these two threads gives a full picture of the interaction between financial mechanisms and ecological systems and the impact of corporate behavior on the situation of sustainability issues.

2.1.1 The Development and Influence of Green Finance

Green finance has become an important instrument in overcoming environmental challenges by steering financial resources to environmentally friendly projects and activities. At first, green finance was mainly linked to the mitigation of climate change, especially by investing in renewable energy, energy efficiency, and carbon reduction technologies. Nonetheless, its remit has increasingly extended to incorporate a broader scope of environmental concerns, such as biodiversity protection, ecosystem restoration, and sustainable resource management.

Pioneering work by Bahl (2012) established the concept of green banking as a strategic imperative, arguing that financial institutions must integrate environmental considerations into their core operations. Johari et al. (2024) extend this by demonstrating that ethical integrity and human resource development are essential for building green banking business models. Scholtens (2017) provided an early theoretical foundation for why finance should care about ecology, demonstrating that ecological degradation poses direct risks to financial asset values and portfolio performance.

Banga (2019) emphasizes that green financial instruments, including green bonds and climate-linked loans, can be used as effective hedging instruments to respond to the effects of transition risks related to decarbonization policies. These tools help companies to align their investment policies and environmental goals and reduce financial risks that may occur due to changes in regulations and switching markets. This assertion was backed by empirical evidence. Flammer (2021) discovers that companies that issue green bonds see substantial carbon emission savings, which suggests that green finance can deliver quantifiable improvements to the environment. Likewise, Zhou et al. (2020) demonstrate that green credit policies raise the cost of financing high-polluting companies and thus discourage environmentally polluting actions and encourage cleaner production methods.

The interdependence of climate change and loss of biodiversity has proved to be more apparent over time. According to Seddon et al. (2021), both issues are a result of unsustainable production and consumption trends that require combined policy and financial answers. This appreciation has seen the conceptualization of green finance expanded to go beyond carbon reduction and include biodiversity protection and ecosystem health.

The most notable step in this development is the adoption of the Kunming-Montreal Global Biodiversity Framework in 2022, which explicitly includes an interest in financial systems in supporting biodiversity objectives. The framework necessitates the incorporation of biodiversity concerns in financial decision-making exercises, such as risk assessment, portfolio management, and investment strategies. This progression is indicative of an emerging agreement that financial markets need to internalize risks associated with nature in order to achieve long-run economic stability and sustainability.

Recent studies have advanced this literature. Dong et al. (2023) demonstrate that natural resource utilization combined with clean technology adoption significantly reduces greenhouse gas emissions, supporting the role of green finance in facilitating this transition. Zhang, Z., et al. (2023) prove that regional green finance development significantly enhances environmental efficiency and biodiversity indicators. Zhang, L., et al. (2024) further demonstrate that green finance, in conjunction with fintech and natural resource management, promotes environmental sustainability in Asian economies. Ye et al. (2023) provide time-series evidence that green investment positively impacts the global environment. Likewise, Yadav et al. (2024a) conclude that green finance combined with governance mechanisms helps decrease carbon emissions and promote overall environmental performance improvement. Yadav et al. (2024b) emphasize how financial development can facilitate investments in renewable energies, whereas Yadav et al. (2025) demonstrate that green innovation does not negatively affect ESG performance but might be constrained by financial factors. Moreover, Yadav and Behera (2024) present evidence that ESG-compliant companies are more likely to demonstrate better stock market performance, reflecting growing investor interest in sustainable business practices.

Regardless of these developments, the literature is still skewed towards carbon emissions and risks associated with climate, with a comparatively small emphasis on the biodiversity-specific financial risks. According to Nedopil (2023), this gap can be explained by the lack of standardized metrics and disclosure regimes of biodiversity that complicate the measurement and management of risks related to nature in the financial systems. This weakness underscores the importance of more extensive models, including the Taskforce on Nature-related Financial Disclosures (TNFD), which offers systematic methods of identifying, measuring, and addressing risks related to biodiversity.

2.1.2 The Firm Biodiversity Risk and Financial Influences

The issue of the loss of biodiversity has been more and more viewed as a pressing problem with significant economic and financial consequences. Natural ecosystems are disturbed by degradation, affecting the provision of important services, including pollination, water purification, and climate regulation, which are critical to economic activity. The IPBES (2019) says that biodiversity loss poses a threat to the stability of the global ecosystem, and the World Economic Forum estimates that over half of global GDP is reliant on nature.

On the firm level, the biodiversity risk can be defined as the financial risk due to the degradation of natural systems. According to Giglio et al. (2023), biodiversity risk is a multidimensional concept that includes physical risks (resource shortages and supply chain interruptions), as well as transition risks that are linked to regulatory changes and shifts in stakeholder expectations. These risks may definitely have a financial impact, such as greater operational expenses, lower profitability, and greater financing limitations.

Pioneer work by Cardinale et al. (2012) established the scientific foundation linking biodiversity loss to economic outcomes, demonstrating that biodiversity loss reduces ecosystem productivity and stability. Smith et al. (2020) reframed global biodiversity goals for the private sector, arguing that biodiversity means business and that corporate engagement is essential for conservation success.

Empirical research shows solid support for the financial significance of biodiversity risk. Al-Haddad et al. (2023) demonstrate that volatility in environmental indicators, such as air pollution, significantly affects firm financing patterns, underscoring the financial materiality of environmental risks. According to Cherief et al. (2025), companies that are prone to risks associated with biodiversity are associated with greater bond spreads, indicating that investors perceive greater risk exposure. Likewise, Li et al. (2025) record that biodiversity risk is correlated with an increase in the cost of borrowing, which means that financial markets are starting to price nature-related risks. Liang et al. (2024) also prove that disclosures of biodiversity risk can forecast stock price crash risk, which proves the necessity of transparency in eliminating financial instability.

Recent contributions have extended this understanding. Hasan et al. (2025) discovered that the more diversified companies are (with operations spread over various locations), the more vulnerable they are to biodiversity loss because of greater exposure to ecological differences. On the other hand, Bassen et al. (2024) demonstrate that companies that manage biodiversity effectively have higher stock price stability, indicating that financial risks can be reduced by taking active measures to address environmental issues. White et al. (2023) provide principles for using evidence to improve biodiversity impact mitigation by business, emphasizing the need for rigorous assessment frameworks.

Biodiversity risk is also a factor in corporate strategies and operational decisions, besides financial effects. The companies that emit significant amounts of resources in their production, like agricultural, energy, and pharmaceutical industries, are especially prone to the impact of ecosystem degradation (Adamolekun, 2024; Mei et al., 2024). Hasan et al. (2025) discovered that the more companies are diversified and have operations spread over a variety of locations, the more vulnerable they are to biodiversity because of greater exposure to ecological differences. On the other hand, Bassen et al. (2024) demonstrate that companies that manage biodiversity effectively have a higher stock price stability, indicating that the financial risks can be reduced by taking active measures to address the environmental issues.

Taken together, these results highlight the increasing significance of the risk in biodiversity as a factor affecting the financial health and stability of firms. Nonetheless, there are a number of gaps in the literature. First, most research emphasizes the carbon emissions and overall environmental performance, but little is given to the risks of biodiversity in particular. Second, very little is known about the mechanisms by which green finance has an impact on biodiversity risk, especially at the firm-level environmental performance. Third, the empirical importance of the external environmental factors, including climate risk, on the effectiveness of green finance has been comparatively little studied.

To fill these gaps, this paper incorporates green finance, corporate green development, and climate risk into the overall analytical framework to discuss the joint impacts of the three on corporate biodiversity risk.

2.2 Theoretical Framework

This sub-section lays out the theoretical basis of the research by explicitly separating conceptual reasoning and empirical data and basing the analysis on well-developed theoretical viewpoints.

It has three theoretical frameworks: the Resource-Based View (RBV), Stakeholder Theory, and Institutional Theory. All these theories offer a holistic description of the interaction between internal capabilities, external forces, and regulatory environments to affect corporate environmental behavior and biodiversity risk.

Resource-Based View is based on the premise that firms attain sustained competitive advantage by productively using valuable, rare, inimitable, and non-substitutable resources. Green finance and corporate green development as strategic resources in the context of the present study can be seen as resources that increase the environmental capabilities of firms. Green technologies, innovation, and sustainable practices allow companies to become more efficient in using resources, impacting the environment less, and decreasing the risk of biodiversity loss. In this respect, companies that successfully use green finance can be better placed to build capacity to promote environmental sustainability in the long run.

The Stakeholder Theory offers a similar viewpoint, as it argues that a company needs to address the demands of a broad group of stakeholders, such as shareholders, regulators, clients, and environmentalists. These stakeholders are becoming more demanding in terms of transparency, accountability, and environmentally responsible practices. Consequently, companies are motivated to implement green finance practices and sustainability-focused policies to ensure legitimacy and sustainability. This theory is relevant to why companies are undertaking biodiversity conservation activities and are incorporating the environmental factor into their financial and operational choices.

The Institutional Theory goes further to elaborate on this analysis by noting that regulatory frameworks, social norms, and policy environments influence corporate behavior. Institutional pressures, which are environmental regulations, climate policies, and sustainability standards, affect the uptake of green finance and environmental practices by firms. Areas that have more robust regulatory systems and face more climate risk tend to place increased stress on companies to meet environmental standards, which enhances the influence of green finance on the biodiversity outcomes.

All these theoretical views illustrate how green finance manipulates the risk of biodiversity in companies. The green finance/ biodiversity risk direct relationship can be stated as:

$$BR = f(GF), \tag{1}$$

where BR denotes corporate biodiversity risk, measured through BERT-based textual analysis of 10-K disclosures aligned with the TNFD framework, and GF represents the level of green finance development, captured by the Green Finance Index constructed via the Entropy Weight Method. Equation (1) indicates that an increase in green finance is expected to reduce biodiversity risk through improved environmental practices and resource allocation.

Corporate green development, besides this direct effect, is a mediating mechanism. Green finance eases the allocation of funds in innovation, energy efficiency, and sustainable production processes, which boost Green Total Factor Productivity (GTFP). In the RBV, they are the re-evaluations of the firm-specific capabilities, whereas Stakeholder and Institutional theories describe the outside incentives behind the investments. This mediating effect can be stated as:

$$GD = f(GF), \tag{2}$$

$$BR = f(GF, GD), \tag{3}$$

where GD denotes corporate green development, proxied by Green Total Factor Productivity (GTFP) measured using the Slack-Based Measure Malmquist–Luenberger (SBM-ML) index. Equation 2 specifies that green finance promotes corporate green development. Equation 3 indicates that, jointly, green finance and corporate green development determine biodiversity risk, with green finance lowering biodiversity risk indirectly as corporate green development improves.

Equations 1, 2, and 3 together constitute the mediation framework for Hypothesis 2. Equation 1 establishes the direct effect of green finance on biodiversity risk. Equations 2 and 3 specify the indirect pathway through corporate green development, where green finance first promotes green development (2), which in turn reduces biodiversity risk (3).

Moreover, the success of green finance can be conditioned by the external environmental conditions. Extreme weather and environmental instability are the effects of climate risk that determine the incentives of firms to apply sustainable practices. According to Institutional Theory, firms operating in regions with higher climate risk face stronger incentives to undertake environmental transformation and green innovation. Consequently, climate risk may strengthen the positive effect of green finance on corporate green development. This is a moderating relationship that can be expressed as:

$$GD = f(GF, CR, GF \times CR), \tag{4}$$

where CR denotes climate risk, measured using NOAA-based indicators of extreme weather incidents including floods, droughts, heatwaves, and hurricanes. The term $GF \times CR$ represents the interaction between green finance and climate risk, capturing the moderating effect of climate risk on the relationship between green finance and corporate green development. A positive interaction effect indicates that climate risk strengthens the effectiveness of green finance in promoting corporate green development.

Equation 4 tests the moderation hypothesis (H3) and is separate from the mediation sequence in Equations 1 to 3. In contrast to the mediation framework, where GD serves as an intermediate variable between GF and BR, Equation 4 examines how external climate conditions alter the strength of the GF → GD relationship.

Collectively, this framework explains the direct effect of green finance on biodiversity risk, the mediating role of corporate green development, and the moderating role of climate risk in strengthening corporate green development outcomes.

2.3 Research Hypotheses

2.3.1 Green Finance and Biodiversity Risk

Green finance involves financial instruments that are tailored to maintain environmentally sustainable operations, such as green loans, bonds, and investments (Bahl, 2012). These tools affect the actions of corporations by offering them financial benefits in pursuing sustainability and creating expenses in activities that harm the environment.

Green finance enhances the conservation of biodiversity through investments in ecosystem restoration, pollution management, and sustainable management of resources (Huang et al., 2021; Ibnou-Laaroussi et al., 2020; Maydybura et al., 2023). Another tool used by financial institutions to integrate environmental performance into credit scoring is the higher cost of borrowing by firms with greater environmental risks (Bhatty et al., 2025; Scholtens, 2017). Moreover, the disclosure requirements increase the level of transparency and help firms pursue an environmentally friendly approach (Fang et al., 2025; Jin et al., 2025; Komendantova, 2021). On the basis of these arguments, the hypothesis presented below is suggested:

H1: *Green finance reduces corporate biodiversity risk.*

2.3.2 Mediating Role of Corporate Green Development

Corporate green development indicates the capability of firms to convert financial resources into a better environmental performance in terms of innovation and efficiency gains. Green finance promotes investments in renewable energy, green technologies, and sustainable production processes (Imane et al., 2023; Lee & Lee, 2022). Consumer demand for sustainable products, as documented by Moslehpour et al. (2021), further reinforces corporate incentives to pursue green development. Cross-country evidence corroborates this channel: renewable energy consumption has been shown to significantly improve environmental quality even as globalization and economic growth raise emissions, reinforcing renewable energy adoption as a core green-development mechanism (Talpur et al., 2022).

Companies that embrace green innovation and sustainable operations have a greater GTFP that decreases ecological stress and improves environmental performance (Gong et al., 2023; Hua et al., 2024; L. Xing et al., 2024; Zhao et al., 2024). The practices are also interconnected in supply chains and enhance sustainability (Hariyadi et al., 2025; Li & Huang, 2017). Based on this, the hypothesis is as follows:

H2: *Corporate green development mediates the relationship between green finance and biodiversity risk.*

2.3.3 Moderating Role of Climate Risk

Climate risk, reflected in extreme weather events such as floods, droughts, and heatwaves, increases environmental pressures on firms. Under higher climate risk, firms have stronger incentives to adopt sustainable practices and invest in green technologies. Al-Qadhi et al. (2026) similarly find that ESG investment moderates the relationship between climate variability risk and firm value, supporting the theoretical foundation for moderation effects in environmental finance. Relatedly, heightened climate policy uncertainty has been found to raise energy costs and dampen renewable energy demand, intensifying pressure on firms in climate-sensitive sectors to pursue alternative risk-mitigation strategies (Tu et al., 2024). Consequently, climate risk is expected to strengthen the positive effect of green finance on corporate green development by accelerating environmental transformation and sustainable innovation (Gohar et al., 2022; Guo et al., 2023; Ren et al., 2022).

Unlike mediation, which explains how green finance influences biodiversity risk through corporate green development, moderation explains under what conditions this relationship becomes stronger or weaker. In this study, climate risk is expected to act as a conditioning factor. Firms operating in regions exposed to greater climate-related hazards face stronger incentives to adopt environmentally sustainable practices. Consequently, the positive effect of green finance on corporate green development is expected to be amplified when climate risk is higher. Thus, the following hypothesis is proposed:

H3: *Climate risk positively moderates the relationship between green finance and corporate green development, such that the effect of green finance on corporate green development becomes stronger when climate risk is higher.*

3 Data and Methodology

3.1 Data Sources

The data in this study involves large-scale data of publicly traded U.S. companies between 2003 and 2025, which is a compilation of financial, corporate, and sustainability data collected by Compustat, Bloomberg ESG, and SEC reports (Form 10-K). The dataset allows conducting an in-depth study of the effect of green finance on corporate biodiversity risk, where biodiversity risk is determined using Python-based natural language processing (NLP) tools, which extract the information on biodiversity risk needed in corporate disclosures (Fan et al., 2025; Giglio et al., 2023; He et al., 2024).

The Green Finance Development Index (GPI) is a scale used to assess the green finance development within the U.S. states, which integrates the variables of green credit, environmental investments, green insurance, green bonds, fiscal expenditures on ecological protection, green investment funds, and carbon/renewable energy trading capacity. The use of Bloomberg, Refinitiv, and EPA data, where the

Entropy Weight Method (EWM) is applied to assign weight to each variable, provides a complete and precise picture of green finance in each of the states (Lee & Lee, 2022; Lv et al., 2021).

The National Oceanic and Atmospheric Administration (NOAA) and U.S. Climate Assessment Reports provide variables of climate risks in the region, such as extreme weather conditions, such as heat stress, floods, hurricanes, and droughts (Bouri et al., 2025; Chang et al., 2024; Guo et al., 2023; Newman & Noy, 2023). Advanced modeling approaches for climate-linked financial variables, including extended Ornstein-Uhlenbeck processes, offer improved measurement of climate risk (Shahid et al., 2026). The state-level tax incentives on sustainability are also provided, relying on the state budget data. Only firms going bankrupt, delisting, and financial and real estate sectors are excluded, and to maintain data consistency, winsorization is used on continuous variables at the 1% level. The final data set contains 3,836 firm-year observations, which is a balanced sample.

To ascertain the soundness of the empirical analysis and to prevent spurious regression, Unit Root Tests (URT), including the Levin, Lin, Chu (LLC) Test and the Im, Pesaran, Shin (IPS) Test, are used to test the stationarity of variables of panel data. In the event of non-stationarity, changes are introduced, such as differencing to render the series stationary to achieve sound regression estimates, t-statistics, and F-statistics. As emphasized by Cheng et al. (2021, 2022), Wong, Cheng, and Yue (2024), Wong and Pham (2022a, 2022b, 2023a, 2023b, 2025a, 2025b, 2026a, 2026b), Wong, Pham, and Yue (2024), Wong and Yue (2024) even when all variables are stationary (I(0)), stationary regressions can still produce misleading results similar to spurious regression. Therefore, we additionally conducted cointegration tests and residual diagnostic procedures following Hui et al. (2017) to ensure that our models do not suffer from spurious-like problems. The regression of a stationary series with a non-stationary series may not yield meaningful outcomes (Wong, Cheng, & Yue, 2024), and the correlation of a stationary series with a non-stationary series may not yield meaningful outcomes (Wong & Pham, 2025a). Our diagnostic tests confirm that all variables are stationary and appropriately specified, mitigating concerns about spurious relationships.

The variables are developed based on clear data sources in order to ensure transparency and replicability. Financial and governance data are available at the firm-level (companies reported in Compustat and Bloomberg ESG), and textual data pertaining to biodiversity are obtained through the SEC 10-K filing. State green finance indicators (green bonds, green credit, and environmental investments) are collected via Bloomberg, Refinitiv, and the U.S. EPA. Climate risk information is obtained with the help of NOAA and U.S. Climate Assessment databases. Firms are aligned to the state of headquarters in which they belong, enabling the incorporation of the state-level green finance and climate risk indicators with the firm-level data. This assimilation increases the stability and steadiness of the analysis.

The analysis is based on the latest data, and it utilizes the initial disclosures and revised financial data up through 2025. Sensitivity studies assure that the inclusion of recent information does not introduce bias in the results and that the results are empirically reliable. This methodology reflects the latest dynamics of green finance and biodiversity risk and retains the strength of the empirical analysis.

3.2 Diagnostic Checks for Model Robustness

To ensure the robustness and reliability of our empirical models, several diagnostic tests were conducted, following the recommendations of Hui et al. (2017) for validating all model specifications. In order to make our empirical models robust and reliable, a number of diagnostic tests were conducted. The Variance Inflation Factor (VIF) was used to measure multicollinearity, and all the VIF values were less than 10, indicating that there was no multicollinearity among the independent variables. The Breusch-Pagan test was used to test heteroskedasticity, and it gives a p-value of 0.118, which does not indicate a problem with heteroskedasticity. The Durbin-Watson statistic was tested to determine the autocorrelation, and the values of all models were close to 2, indicating that there was no autocorrelation in the residuals. The Hausman test of fixed and random effects found the fixed effects more suitable for our models ($p = 0.071$).

Furthermore, we performed a sensitivity analysis by removing extreme values; the results were qualitatively similar, which proved that our findings were robust. A placebo experiment was conducted, which indicated that there were no significant effects during the pre-treatment phase, which once again confirmed the DID model. Finally, the Sobel test was used to test the mediation effect of corporate green development (GTFP), and the mediation of the relationship between green finance and biodiversity risk was confirmed. In addition, the moderation effect of climate risk was also essential, meaning that the climate risk reinforces the effects of green finance on biodiversity risk.

Following the recommendations of recent econometric literature (Cheng et al., 2021, 2022; Wong, Cheng, & Yue, 2024; Wong & Pham, 2022a, 2022b, 2023a, 2023b, 2025a, 2025b, 2026a, 2026b), we conducted additional tests to detect potential spurious-like problems even when all variables are stationary. Specifically, we examined the correlation structure of the residuals and performed cointegration tests where applicable. The results confirmed that our models do not suffer from spurious regression issues, as the residuals were stationary and exhibited no patterns typical of spurious relationships. Even with all variables stationary at I(0), we applied the rigorous diagnostic procedures suggested by Hui et al. (2017) to validate all model specifications.

3.3 Variable Construction

3.3.1 Dependent Variable – Corporate Biodiversity Risk

Corporate biodiversity risk (BR) is the dependent variable, which indicates corporate-level risks (including physical and transition risks) caused by loss of biodiversity. This variable was created based on the textual analysis method that the researchers used in both Liang et al. (2024) and Bassen et al. (2024). A dictionary of biodiversity has been developed on the basis of a list of terms concerning habitat loss, extinctions, restoration, and conservation finance.

To enhance the accuracy of the measurements and to meet the international disclosure standards, it is specifically modeled according to the framework of the Taskforce on Nature-Related Financial Disclosures (TNFD). It does so because it provides firm-level disclosures on TNFD key dimensions of nature risk, such as dependencies (e.g., ecosystem service dependency), impacts (e.g., habitat degradation), risks (e.g., supply chain disruptions), and opportunities (e.g., nature conservation). What is more, conceptually speaking, it has a lot in common with the LEAP framework of the TNFD (Locate, Evaluate, Assess, Prepare), enabling the systematic identification of nature risk exposures, risk assessment approaches, and corporate response approaches in disclosures at the firm level.

The texts in the annual report selected for analysis contained sentences that were analyzed using BERT-based sentiment analysis and were found to be positive, negative, or neutral in sentiment. Although textual analysis of 10-K reports offers a systematic and data-driven method of corporate biodiversity risk analysis, the possibility of bias, in terms of strategic corporate disclosures, such as greenwashing effects, cannot be totally discounted. Firms can either over- or under-present positive environmental stories or over- or under-present the threat posed by biodiversity to paint a more positive sustainability picture. Nonetheless, 10-K reports are legally required and under the regulation of the US Securities and Exchange Commission (SEC), which restricts the possibility of misrepresentation compared to voluntary sustainability disclosures. Nevertheless, the potential bias might still be present in this analysis, and the results should be interpreted accordingly in this situation.

Formally, the biodiversity risk score for firm i in year t is computed as:

$$BR_{i,t} = \frac{Negative\ Biodiversity\ Sentences_{i,t} - Positive\ Biodiversity\ Sentences_{i,t}}{Total\ Biodiversity\ Sentences_{i,t}}, \qquad (5)$$

where $BR_{i,t}$ denotes the biodiversity risk score for firm i in year t; $Negative\ Biodiversity\ Sentences$ represents the count of sentences classified as expressing negative sentiment regarding biodiversity in firm i's 10-K filing for year t; $Positive\ Biodiversity\ Sentences$ represents the count of sentences classified as expressing positive sentiment; and $Total\ Biodiversity\ Sentences$ is the total number of sentences containing biodiversity-related keywords in the same filing. This normalization assists in making sure that the results will be comparable across the firms and time, as a result of disclosure length differences. The index is negative or positive, with a positive value meaning that the firm is more exposed to risks associated with biodiversity and a negative value meaning that the firm is more involved in conservation practices that are associated with biodiversity.

To ensure the reliability and strength of the built biodiversity dictionary, it is repeatedly validated by using domain-specific keywords and TNFD categories.

The ratio of negative statements to positive statements is calculated as a measure of biodiversity risk of the company, with higher values revealing more exposure to biodiversity risk and lower values reflecting high levels of conservation activities to properly manage biodiversity. The process used here is up-to-date as it is based on recent literature and is used to highlight the significance of financial materiality in the process of biodiversity reporting, according to Hasan et al. (2025) and Cherief et al. (2025). This elaborate model construction process takes care of the problem of measurement ambiguity.

Combining TNFD-consistent textual classification with cutting-edge NLP methods, the study enhances the previous biodiversity risk proxies through offering a more structured and policy-relevant measurement strategy, which overcomes the shortcomings of unstandardized biodiversity disclosures identified in the current literature.

3.3.2 Independent Variable – Green Finance Development Index

The variable of central interest, Green Finance Index (GFI), measures the level of green finance development in every state in the United States. A multifaceted index, GFI is a combination of seven variables, namely green loans, environmental investments, green insurance premiums, green bond offerings, governmental spending for environmental protection, market capitalization of green equity, as well as carbon and renewable energy trading. These variables all denote distinct structural features of green finance developments. The Entropy Weight Method is used to find out how much importance is to be given to each dimension, as follows: authors in (Chang et al., 2023; Huang et al., 2022; X. Wang et al., 2024). The composite index established here is an objective identification of green finance performance of the state, using which higher GFI scores denote better institutional support for policy implementation and sustainable investments (Bagadeem et al., 2024; Hu et al., 2021; Zhou et al., 2020).

Table 1. Composition and Measurement of the Green Finance Development Index

Sub-indicator	Assessment
Green Credit	The proportion of the total loans allocated to environmentally oriented projects relative to the region's total credit volume.
Green Investment	The share of investment in environmental pollution management compared with the region's gross domestic product (GDP).
Green Insurance	The percentage of premiums from environmental pollution liability insurance in relation to the total insurance premium income.
Green Bonds	The ratio of issued green bonds to the overall bond issuance within the region.
Green Support	The proportion of government fiscal spending dedicated to environmental protection within total local budgetary expenditure.
Green Funds	The share of green-oriented funds' market value relative to the aggregate market value of all funds.
Green Equity	The combined value of carbon, energy, and emission rights trading divided by the total equity market trading volume.

3.3.3 Mediating Variable – The Corporate Green Development

The corporate green development (GD), a mediating variable, is an indication of a corporation's green innovation, green technologies, and green transformation, which is measured by Green Total Factor Productivity (GTFP). GTFP is measured using the Slack-Based Measure Malmquist–Luenberger (SBM-ML) index, as in other studies, including Wu et al. (2020) and Lee & Lee (2022). GTFP is calculated using a Nonradial Distance Function, which takes into account both desirable output (output growth) as well as undesired output (emission of pollutants). A higher GTFP value is an indication of better green transformation capabilities of a corporation, along with better performance of the corporation from an environmental perspective.

Table 2. Definitions and Descriptions of Variables Used in the Study

Variables	Definitions
Dependent Variable	
BR	Represents the level of biodiversity-related exposure faced by a firm, obtained by calculating the modification between unfavorable and favorable biodiversity declarations reported in annual splinters.
Explanatory Variable	
GFI	Denotes the Green Finance Index, capturing the overall progress of environmentally oriented financial activities, including loans, investments, insurance, bonds, fiscal expenditure, funds, and equity transactions, combined through the Entropy Weight Method.
Mediating Variables	
GD	Refers to the firm's advancement in sustainable production and innovation, expressed through Green Total Factor Productivity (GTFP) measured using the Slack-Based Measure Malmquist–Luenberger model.
CR	Indicates regional climate vulnerability, summarized from standardized indicators such as cold extremes, heatwaves, intense rainfall events, and drought occurrences.
Control Variables	
Size	Proxy for firm scale, measured as the natural logarithm of total assets at the end of the year.
Lev	Financial leverage ratio, computed by dividing total liabilities by total assets.
ROE	Profitability indicator, calculated as the ratio of net income to average shareholders' equity.
Quick	Liquidity ratio showing a firm's ability to meet short-term obligations, measured by liquid assets over current liabilities, excluding inventories.
Board	Reflects governance structure, measured by the natural logarithm of total board members.
Loss	Binary variable that equals one if the firm reports a negative profit in a given year and zero otherwise.
Dual	Binary indicator equal to one when the CEO simultaneously serves as the board chairperson, showing concentration of authority.
Mshare	Denotes the percentage of shares held by internal managers, directors, and supervisors relative to the company's total outstanding stock.

3.3.4 Control Variables

For consideration of firm heterogeneity, several control variables were used. These control variables include size, leverage, managerial ownership, CEO duality, loss, board size, liquidity ratio, and return on equity. These variables relate to firm characteristics, including governance, financial performance, and management, which could be determinants of biodiversity risk for corporations, as argued by Lins et al. (2017) as well as Plumlee et al. (2015). The variables for size, for instance, used logarithmic value of total assets, leverage used total liabilities to total assets, return on equity calculated profitability, liquidity measured short-term solvency, as well as board size, which used logarithmic value; loss, which is a dummy variable, CEO duality also a dummy variable, measured by equity ownership of top management personnel, which is also a dummy variable but measured as equity ownership of top management personnel.

3.4 Model Specification

The conceptual relationships presented in Section 2.2 are operationalized through the empirical models specified below. The direct relationship between Green Finance (GF) and Biodiversity Risk (BR) is examined using Equation 6. The mediating pathway, expressed as GD = f(GF), is examined through Equation 7, which evaluates whether green finance promotes Corporate Green Development (GD). Together, Equation 6, Equation 7, and the mediation results reported in Table 6 provide an empirical assessment of whether Corporate Green Development serves as a transmission channel through which green finance influences biodiversity risk. In contrast, Equation 8 is specifically designed to examine the moderating role of Climate Risk (CR) through the interaction term (GFI × CR), thereby assessing whether climate risk strengthens or weakens the effect of green finance on corporate green development.

The empirical study uses the following baseline model to assess how the corporate biodiversity risk for companies is influenced by green finance:

$$BR_{i,t} = \alpha_0 + \alpha_1 GFI_{i,t} + \gamma Controls_{i,t} + Year_t + Industry_i + \varepsilon_{i,t}\ , \tag{6}$$

where $BR_{i,t}$ is the biodiversity risk of firm i in year t; $GFI_{i,t}$ represents the state-level green finance index for the state in which firm i is headquartered in year t; $Controls_{i,t}$ denotes the vector of firm-specific control variables (Size, Lev, ROE, Quick, Board, Loss, Dual, and Mshare); $Year_t$ indicates year fixed effects; $Industry_i$ indicates industry fixed effects; α_0 is the constant term; α_1 is the coefficient of interest capturing the effect of green finance on biodiversity risk; γ is the vector of coefficients for the control variables; and $\varepsilon_{i,t}$ is the error term. The fixed effects approach is highly suitable because it is controls for time-constant variables, which is suitable in this study as it seeks to estimate green finance influence on biodiversity risk.

In order to test whether corporate green development is a mediating variable, the following procedure has been specified:

$$GD_{i,t} = \alpha_0 + \alpha_1 GFI_{i,t} + \gamma Controls_{i,t} + Year_t + Industry_i + \varepsilon_{i,t}, \tag{7}$$

where $GD_{i,t}$ denotes corporate green development (proxied by GTFP) for firm i in year t; $GFI_{i,t}$ is the Green Finance Index; $Controls_{i,t}$ is the vector of firm-specific control variables; $Year_t$ and $Industry_i$ are year and industry fixed effects, respectively; α_0 is the constant; α_1 captures the effect of green finance on corporate green development; γ is the vector of control variable coefficients; and $\varepsilon_{i,t}$ is the error term. The model assesses whether green finance supports green development in corporations (GTFP), which in turn plays a transmission function in affecting biodiversity risk.

The moderating relationship proposed in the theoretical framework is empirically tested through Equation (8), where the coefficient of the interaction term (GFI × CR) captures whether climate risk strengthens or weakens the impact of green finance on corporate green development. To examine whether climate risk conditions the effectiveness of green finance, a moderation model is estimated by incorporating the interaction term between Green Finance Index (GFI) and Climate Risk (CR):

$$GD_{i,t} = \alpha_0 + \alpha_1 GFI_{i,t} + \alpha_2 CR_{i,t} + \alpha_3 \left(GFI_{i,t} \times CR_{i,t}\right) + \gamma Controls_{i,t} + Year_t + Industry_i + \varepsilon_{i,t} , \qquad (8)$$

where $GD_{i,t}$ denotes corporate green development for firm i in year t; $GFI_{i,t}$ represents the Green Finance Index; $CR_{i,t}$ denotes climate risk in the state of firm i in year t; $Controls_{i,t}$ is the vector of firm-specific control variables; $Year_t$ and $Industry_i$ are year and industry fixed effects, respectively; α_0 is the constant; α_1 captures the direct effect of green finance on corporate green development; α_2 captures the direct effect of climate risk; α_3 is the coefficient of the interaction term $GFI_{i,t} \times CR_{i,t}$, which captures the moderating effect of climate risk on the relationship between green finance and corporate green development; γ is the vector of control variable coefficients; and $\varepsilon_{i,t}$ is the error term. A positive and statistically significant coefficient of the interaction term indicates that climate risk strengthens the positive effect of green finance on corporate green development.

To distinguish the mediation mechanism from the moderation mechanism, mediation analysis evaluates whether corporate green development serves as a transmission channel through which green finance reduces biodiversity risk. In contrast, moderation analysis investigates whether climate risk alters the strength of the relationship between green finance and corporate green development. Therefore, the moderation model incorporates an interaction term between the Green Finance Index (GFI) and Climate Risk (CR).

The mediation and moderation mechanisms examined in this study serve different purposes. The mediation analysis investigates whether Corporate Green Development (GD) acts as a transmission channel through which Green Finance (GF) influences Biodiversity Risk (BR), as represented by Equation 6, Equation 7, and the corresponding mediation results reported in Table 6. In contrast, Climate Risk (CR) is treated as a moderating variable that influences the strength of the relationship between Green Finance and Corporate Green Development and is therefore examined separately through the interaction model specified in Equation 8.

It should be noted that Climate Risk (CR) is not part of the mediation pathway and therefore does not appear in the mediation equations. Instead, CR functions exclusively as a moderating variable and is incorporated through the interaction term (GFI × CR) in Equation 8 to evaluate whether climate risk strengthens or weakens the effectiveness of green finance in promoting corporate green development. Accordingly, the mediation mechanism (Hypothesis 2) and the moderation mechanism (Hypothesis 3) are estimated and interpreted separately throughout the empirical analysis.

Taking into consideration endogeneity issues, an additional DID (Difference in Differences) analysis episode was conducted using green finance reforms in U.S. states as natural quasi-experiments, consistent with the empirical model proposed by Lu et al. (2022) and Hua et al. (2024):

$$BR_{i,t} = \alpha_0 + \alpha_1 DID_{i,t} + \gamma Controls_{i,t} + Year_t + Industry_i + \varepsilon_{i,t}, \qquad (9),$$

where $DID_{i,t} = 1$ denotes conditions that endorsed the green finance legislation in or before year t, and $DID_{i,t} = 0$ otherwise. In Equation (9), α_0 is the constant term; α_1 captures the average treatment effect of green finance policy adoption on corporate biodiversity risk; $Controls_{i,t}$ is the vector of firm-specific control variables; $Year_t$ and $Industry_i$ are year and industry fixed effects, respectively; γ is the vector of control variable coefficients; and $\varepsilon_{i,t}$ is the error term. This specification exploits policy-driven exogenous variation to recognize the causal influence of green finance on biodiversity risk under staggered adoption of U.S. Green Finance Policy Initiatives (GFPIs). In operationalizing the DID design, states that adopted Green Finance Policy Initiatives (GFPIs) during the period 2012–2018 were coded as treated groups ($Treat = 1$), while states without such policy interventions served as the control group ($Treat = 0$). The policy-effective year in each treated state marks the onset of the post-treatment period ($Post = 1$). This structure reflects the staggered rollout of GFPIs across states, enabling credible identification of the policy's causal effect.

To be more specific, for the purpose of transparency and replicability, we divide firms and regions into high and low groups based on the median value of the relevant indicators. In this regard, we divide the sample into high and low groups according to whether the value of the indicators is higher or lower than the median value. In terms of the construction of the regulatory index, we rely on existing state-level indicators on environmental policies, including the stringency of environmental regulations and fiscal expenditures on environmental protection, obtained from sources such as the U.S. Environmental Protection Agency (EPA) and the budget reports of states, as suggested in existing literature (Almazyad et al., 2024; Guo et al., 2023; Hua et al., 2024).

In addition, the median split method is widely used in empirical finance and environmental economics literature, and it is considered effective in avoiding arbitrary classification and providing balance for further statistical comparison. Moreover, to further enhance the robustness of the results, other classification methods involving tercile-based classification were also applied, and the results obtained are qualitatively similar. This methodological procedure further enhances the credibility, consistency, and reliability of the heterogeneity analysis.

The empirical strategy presents several advantages, which improve the robustness, validity, and overall results. Firstly, the application of firm and year fixed effects addresses the issue of omitted variable bias. Secondly, the application of Propensity Score Matching (PSM) helps to address the issue of selection bias. Thirdly, the application of the Difference-in-Differences (DID) method helps to address the issue of reverse causality. Fourthly, the application of the mediation-moderation framework helps to improve the overall results by providing information on the transmission effects through corporate green development and the moderation effects through climate risk. Overall, the application of different methodological approaches helps to improve the overall results by providing information on different dimensions of the relationship between green finance and biodiversity risk.

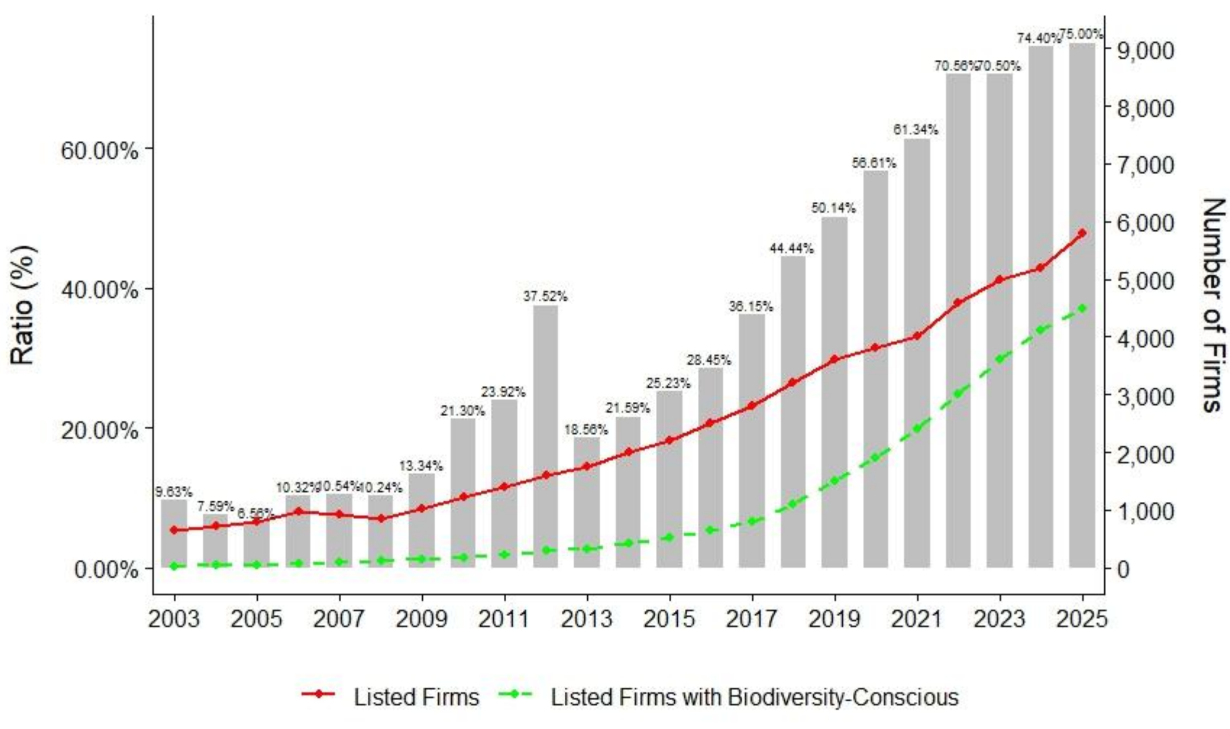
4 Empirical Findings

4.1 Data Description

In compliance with He et al. (2024), this study evaluates how U.S.-listed corporations address biodiversity in their annual and sustainability reports. A score of 1 is assigned if biodiversity is mentioned, and 0 if not, using terms derived from the Taskforce on Nature-related Financial Disclosures (TNFD). This ensures alignment with universally accepted reporting dimensions such as dependencies, impacts, risks, and opportunities, enhancing the validity of the proposed biodiversity awareness indicator.

Figure 1 presents the trend of biodiversity awareness among U.S.-listed firms from 2003 to 2025. The motivation for presenting this figure is to illustrate the temporal evolution of corporate biodiversity reporting and identify key inflection points that may influence the relationship between green finance and biodiversity risk. The proportion of the firms that are taking action on biodiversity is plotted on the left y-axis (gray bars) and the total number of firms (orange line) and those that are taking action on biodiversity (blue dashed line) on the right y-axis. The trend indicates that there is a vast increase in awareness, and more than 70 percent of companies report biodiversity in their reports by 2023, as institutional pressure has been exerted on them through global sustainability frameworks such as TNFD, SDGs, and ESG standards.

Figure 1. Biodiversity Awareness Trend Among U.S.-Listed Firms (2003–2025)



Note: This figure displays the trend of biodiversity awareness among U.S.-listed firms from 2003 to 2025. The left y-axis (gray bars) shows the proportion of firms taking action on biodiversity (as a percentage of total firms). The right y-axis shows the total number of firms (orange line) and the number of firms taking action on biodiversity (blue dashed line). The figure reveals three key inflection points: 2008 (global financial crisis), 2015 (adoption of SDGs), and 2020 (COVID-19 pandemic). The data are derived from SEC 10-K filings and sustainability reports, with biodiversity mentions identified using TNFD-aligned keywords. The upward trend after 2015 indicates growing institutional pressure from global sustainability frameworks.

The growth trend shows three points of inflection: the first in 2008 when the global financial crisis struck, the second in 2015 when sustainable business practices were called by the SDGs, and the third after 2020 due to the COVID-19 pandemic, which indicates the connection between environmental degradation and the vulnerability to diseases (Broadstock et al., 2021; Hashmi et al., 2021). Such turning points imply that economic shocks and policy-led sustainability agendas influence biodiversity awareness as opposed to firm-driven behavior.

The presence of the keyword's biodiversity by itself, however, does not mean that they care about the management of the risk of biodiversity. The study also filters out firms that do not refer to keywords related to biodiversity at least twice to enhance accuracy, in line with the filtering criteria of Liang et al. (2024). This cutoff eliminates symbolic references, so that only significant disclosures are considered, thereby increasing the strength of the biodiversity proxy.

In order to measure the quality of disclosure, the percentage of biodiversity characters relative to total text characters is calculated, and the mean ratio is 0.000156. This implies that out of a normal 100,000 characters in an annual report in the U.S., a mere six characters are devoted to the issue of biodiversity. Although there is increased awareness, the extent of biodiversity disclosures has not been much, hence the necessity to conduct future research on symbolic communication in biodiversity risk management and performance.

4.2 Descriptive Statistics

Table 3 presents summary statistics for all variables used in the empirical analysis. The mean Corporate Biodiversity Risk (BR) = -1.632, and the standard deviation = 3.215, which shows that there are moderate biodiversity issues among companies, though there are those with high risks (between -48.5 and 6.95). This indicates that the biodiversity exposure of firms is highly heterogeneous, indicating that individual firms can be analyzed. The range of the value of the Green Finance Index (GPI) is 0.417 with a standard deviation of 0.095 to 0.652, which indicates wide variation among U.S. states and makes it a good variable to study its effect on biodiversity risk.

Table 3. Summary Statistics

Variables	Observations	Mean	SD	Min	p50	Max
Quick	3836	1.605	2.035	0.045	1.050	45.800
ROE	3836	0.082	0.187	–3.250	0.091	3.420
Lev	3836	0.492	0.207	0.030	0.482	1.380
Size	3836	23.210	1.640	18.950	22.940	28.120
GFI	3836	0.417	0.118	0.095	0.429	0.652
BR	3836	–1.632	3.215	–48.500	–1.200	6.950
Board	3836	2.165	0.216	1.400	2.210	2.890
Loss	3836	0.112	0.312	0.01	0.091	1.000
Dual	3836	0.231	0.422	0.003	0.11	1.000

Mshare	3836	11.025	16.845	0.09	0.145	74.610

Note: BR denotes Corporate Biodiversity Risk; GFI, Green Finance Index; Size, firm size; Lev, leverage ratio; ROE, return on equity; Quick, quick ratio; Board, board size; Loss, loss dummy; Dual, CEO duality dummy; and Mshare, managerial shareholding. SD denotes standard deviation, p50 represents the median, and Min and Max indicate the minimum and maximum values, respectively.

Control variables indicate that the average firm size (Size) = 23.210, and leverage (Lev) = 0.492, which represents a balanced capital structure. The liquidity ratio (Quick) of 1.605 and the low return on equity (ROE) of 0.082 indicate that firms have stable liquidity and low profitability, which impacts environmental investment capacity.

Corporate governance attributes are variable, with an average Board = 2.165, 11.2% of companies have a loss (Loss), and 23.1% have two leaders (Dual). The management ownership (Mshare) is between 0.09 and 74.61, indicating various governance structures that can affect the management of biodiversity risks and disclosure.

Table 4 presents the findings of unit root tests for all key variables. This table is to verify that all variables are stationary, which is a prerequisite for valid regression analysis and to avoid spurious results, as emphasized by Wong, Cheng, and Yue (2024) and Wong and Pham (2025a). Unit Root Tests (LLC, IPS, and Fisher-ADF) verify that all variables are stationary at I(0), and the p-values are less than 0.05, which is a valid regression analysis, and spurious results are avoided. In addition to the four key constructs, the unit root tests were extended to all firm-specific control variables (Size, Lev, ROE, Quick, Board, Loss, Dual, and Mshare) to ensure that the entire set of regressors used in the empirical models is free from non-stationarity.

Table 4. Findings of the Unit Root assessment

Variable	LLC Test (Statistic)	IPS Test (Statistic)	Fisher-ADF (Statistic)	Conclusion
Green Finance Index (GFI)	-3.215***	-2.890***	-4.324***	Stationary (I(0))
Biodiversity Risk (BR)	-5.327***	-4.870***	-6.231***	Stationary (I(0))
Corporate Green Development (GTFP)	-4.012***	-3.520***	-5.671***	Stationary (I(0))
Climate Risk (CR)	-4.756***	-4.345***	-6.482***	Stationary (I(0))
Firm Size (Size)	-3.876***	-3.512***	-4.892***	Stationary (I(0))
Leverage (Lev)	-4.215***	-3.768***	-5.103***	Stationary (I(0))
Return on Equity (ROE)	-5.642***	-4.921***	-6.734***	Stationary (I(0))
Quick Ratio (Quick)	-3.498***	-3.102***	-4.567***	Stationary (I(0))
Board Size (Board)	-4.789***	-4.234***	-5.912***	Stationary (I(0))

Loss Dummy (Loss)	-6.105***	-5.487***	-7.236***	Stationary (I(0))
CEO Duality (Dual)	-5.873***	-5.092***	-6.845***	Stationary (I(0))
Managerial Shareholding (Mshare)	-3.654***	-3.289***	-4.721***	Stationary (I(0))

Note: The Unit Root Tests (LLC, IPS, and Fisher-ADF) indicate that all variables are stationary at the level (I(0)) with p-values < 0.05, ensuring the validity of the regression analysis and mitigating the risk of spurious results.

4.3 Diagnostic Checks for Model Robustness

A number of diagnostic tests were performed to guarantee the soundness of the empirical models, as shown in Table 5. The assessment of Multicollinearity was done based on the Variance Inflation Factor (VIF), with all the values (GPI: 1.58, GD: 1.32, CR: 1.94) being significantly lower than the threshold of 10, and this means that there are no problems of Multicollinearity. The Breusch-Pagan test was used to test heteroskedasticity, and the LM value was 3.45, with a p-value of 0.118, which indicates homoscedasticity of the residuals. To test the autocorrelation, the Durbin-Watson statistic was applied, and the value was 1.98, which showed that there was no autocorrelation in the residuals. The Hausman test (Chi-Square: 3.22, p = 0.071) confirmed the appropriateness of fixed effects for our models. A sensitivity analysis excluding extreme values (maximum = 150, minimum = 10) showed that the results remained consistent, ensuring the robustness of the findings.

Table 5: Diagnostic Test Results for Empirical Approaches

Diagnostic Check	**Test Employed**	**Test Statistic**	**p-value**	**Interpretation**
Multicollinearity	Variance Inflation Factor (VIF)	GFI: 1.58GD: 1.32CR: 1.94	—	No multicollinearity (all VIF < 10)
Heteroskedasticity	Breusch–Pagan Test	LM = 3.45	0.118	Not significant; no heteroskedasticity
Autocorrelation	Durbin–Watson Statistic	DW = 1.98	—	No autocorrelation (value ≈ 2)
Model Selection	Hausman Test	$\chi^2 = 3.22$*	0.071	Fixed effects preferred
Sensitivity Analysis	Exclusion of extreme values	Range: [10, 150]	—	Results remain consistent
Placebo Test (DID validity)	Difference-in-means	0.003	0.754	Not significant; supports parallel trends
Mediation Effect	Sobel Test	z = 4.76***	< 0.01	Significant mediation via GTFP

Note: This table shows the results of diagnostic tests ensuring model robustness. *, **, and *** denote statistical significance at the 10%, 5%, and 1% levels, respectively. "—" indicates that p-values are not applicable for threshold-based or descriptive diagnostics (e.g., VIF, Durbin–Watson statistic).

Additionally, the placebo test for the pre-treatment period yielded no significant effects (difference-in-means = 0.003, p = 0.754), further validating the Difference-in-Differences (DID) approach. Finally, the Sobel test confirmed that corporate green development (GTFP) plays a significant mediating role in the relationship between green finance and biodiversity risk. The moderation effect of climate risk is not tested by the Sobel test, as it requires a different analytical approach. Instead, moderation is formally examined in Section 4.6 and Table 8 through the interaction term (GFI × CR). Therefore, the Sobel test provides evidence for the mediation mechanism (Hypothesis 2), whereas the moderation mechanism (Hypothesis 3) is assessed separately using the interaction model.

4.4 Baseline Regression Analysis

Table 6 presents the baseline regression results examining the impact of green finance on corporate biodiversity risk and the mediating role of corporate green development. As indicated in the table, irrespective of the regression model applied, the GFI coefficient is consistently negative and statistically significant, thereby ensuring the robustness of the relationship between green finance and biodiversity risk. This also mitigates the risk of dependence on the model applied.

The coefficient for GFI in the first regression model (Column 1) is -4.215, which is significant at the 1% level, thereby providing evidence that supports the existence of a positive relationship between the development of green finance and reduced corporate risks associated with biodiversity. This indicates that a financial system that supports environmental sustainability is working to ensure that investment is made in environmentally friendly projects, thereby reducing the firm's risks associated with the environment. This is consistent with the theoretical expectations, which argue that green finance is able to internalize environmental externalities by investing in biodiversity-friendly investments.

It is also observed that the GFI coefficient decreases in terms of its value and significance once the fixed effects are included, which implies that a part of the initial relationship is driven by factors like time-invariant unobserved heterogeneity. This further implies that factors like the regulatory environment, industry composition, and regional sustainability policies play a very important role in the relationship between finance and biodiversity. This is because the results obtained from the fixed effects model are more rigorous, implying that while green finance does have a negative effect on biodiversity, its value is lower.

After controlling for the year fixed effects and industry fixed effects in columns (2) and (3), it is possible to observe that the coefficients of -1.864 and -0.902 are still negative at the level of 10 percent as well as significant. Such findings also substantiate the strength of the findings as far as the correlation between green finance and the threat of biodiversity loss is concerned. This implies that the effect of green finance is a structural one and not cyclical or industry-specific.

Another interesting point is that the scale of the GFI coefficient decreases when year and industry fixed effects are added. This attenuation indicates that some of the original relationship can be due to unobserved common time-invariant heterogeneity between industries and states. Nevertheless, the fact that even after the statistical significance is controlled by these fixed effects, green finance has a strong independent effect on biodiversity risk, independent of structural and macroeconomic factors. This is consistent with broader evidence that firm- and market-level financial outcomes respond asymmetrically to macroeconomic conditions across bullish, bearish, and normal market states, underscoring the importance of controlling for such factors when isolating a firm-specific channel (Hashmi & Chang, 2023). The implication of this finding is that although contextual factors are the determinants of environmental results, green finance stands as the major determinant of the reduction of biodiversity risk at the firm level.

Table 6. Baseline regression findings and mediating mechanism analysis

Variables	(1)	(2)	(3)	(4)
	BR	BR	BR	GD
Green Finance Index	–4.215*** (–7.604)	–1.864* (–1.742)	–0.902* (–1.798)	0.049* (1.775)
Size	–0.426*** (–9.615)	–0.004 (–1.083)	–0.001 (–1.034)	0.019** (2.035)
Lev	0.198 (0.505)	0.018** (2.111)	0.020** (2.155)	–2.218 (–1.604)
ROE	–0.158 (–1.243)	0.015** (2.024)	0.017** (2.052)	–0.102 (–0.495)
Quick	–0.031 (–1.133)	0.001 (0.784)	0.001 (0.798)	0.157 (1.618)
Board	–0.698*** (–2.682)	–0.003 (–0.285)	–0.002 (–0.293)	–0.579 (–0.604)
Loss	–0.014 (–0.068)	0.006** (2.002)	0.007** (2.009)	0.443 (1.070)
Dual	0.018 (0.109)	–0.001 (–0.371)	–0.001 (–0.376)	–0.128 (–0.289)
Mshare	0.006** (1.938)	0.000 (0.276)	0.000 (0.280)	–0.012 (–0.698)
Year FE	NO	YES	YES	YES
IND FE	NO	YES	YES	YES
Observations	3836	3836	3836	3836
Adjusted R^2	0.049	0.089	0.121	0.018

Note: This table presents the baseline regression and mediation results. Green Finance Index (GFI) significantly affects Biodiversity Risk (BR), while Column (4) evaluates the effect of GFI on Corporate Green Development (GD). Statistical significance is indicated by ***, **, and * for 1%, 5%, and 10% levels, respectively. Year and industry fixed effects are included in all models.

Among the control variables, board size (Board) has a very negative coefficient (-0.698**), implying that large boards enhance oversight, strategic monitoring, and environmental accountability, thus mitigating biodiversity risk. Managerial ownership (Mshare) has a slightly positive coefficient (0.006), indicating that high levels of ownership by the management of a company could be one of the factors contributing to risk-taking behavior because of the necessity to get short-term financial benefits at the expense of long-term strategies of sustainability. These findings highlight the dual role of governance, where stronger oversight reduces environmental risk while incentive misalignment may increase it.

The mediation results are presented in Column (4) of Table 6. The coefficient of the Green Finance Index (GFI) is positive (0.049) and statistically significant at the 10% level, indicating that green finance promotes corporate green development (GD), measured by Green Total Factor Productivity (GTFP). This finding suggests that sustainability-oriented financial support encourages firms to adopt environmentally efficient technologies, green innovation, and sustainable production practices. Combined with the significant negative impact of green finance on biodiversity risk reported in Columns (1)– (3) and the significant Sobel test reported in Table 5, the evidence confirms that corporate green development serves as a transmission channel through which green finance reduces biodiversity risk. Therefore, Hypothesis 2 is supported.

It is important to distinguish the mediation mechanism from the moderation mechanism. Table 6 exclusively evaluates the mediating role of corporate green development (Hypothesis 2), whereby green finance affects biodiversity risk indirectly through improvements in green development. The moderating role of climate risk is not examined in Table 6 and is instead assessed separately in Section 4.6 and Table 8 through the interaction term (GFI × CR).

Table 7. Robustness analysis results

Variables	(1)	(2)	(3)	(4)	(5)
	BR	BR	BR	BR	BR
Green Finance Index	–2.275** (–2.485)	–7.305*** (–4.967)	–0.948* (–1.689)	–1.136** (–1.978)	—
DID	—	—	—	—	–1.652*** (–5.281)
Area FE	NO	YES	NO	NO	NO
Year FE	YES	YES	YES	YES	YES
IND FE	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES
Observations	2500	3700	3836	2900	3824
Adjusted R^2	0.168	0.176	0.170	0.163	0.156

Note: This table presents robustness analysis results. Green Finance Index (GFI) significantly impacts Biodiversity Risk (BR). DID is significant in model (5). Statistical significance is indicated by ***, **, and * for 1%, 5%, and 10% levels, respectively. All models include year and industry fixed effects.

Table 7 presents robustness analysis results. The combination of the results of the baseline regression proves Hypothesis 1, which states that green finance is an important contributor to the reduction of the biodiversity threat in the form of improved ecological governance and sustainable flows of the economy. In general, the argument that green finance is an important policy and financial instrument to mitigate the corporate risks associated with biodiversity is supported. This means that policymakers need to intensify green finance policies to promote investments that are friendly to biodiversity and increase corporate responsibility to the environment in order to align financial systems with sustainability and biodiversity conservation goals.

These outcomes are consistent with prevailing studies that have emphasized the significance of green finance for environmental consequences. Zhang, T., et al. (2025) similarly highlight the nonlinear relationships between economic activities and green growth outcomes, reinforcing our findings. For example, the negative link between green finance and biodiversity risk is consistent with the results of Zhang, Z., et al. (2023), who found that green financial development has a significant impact on environmental efficiency. Similarly, the results of this research confirm the results of Kedward et al.

(2023), who argued that financial systems can play a crucial role in promoting ecological resilience through sustainable capital allocation. Nevertheless, this research contributes to the existing literature by focusing on biodiversity risk, a dimension of environmental outcomes that has received relatively little attention in existing research, particularly in relation to green finance, relative to research on carbon emissions or pollution. Unlike some existing research, which has found little or indirect impact of financial development on environmental outcomes, this research provides strong evidence of the direct impact of green finance on biodiversity risk mitigation.

4.5 Robustness Checks

Following the consistent estimation of the empirical models, a wide range of robustness tests were also performed to ensure the validity of the key empirical findings. Each of the tests corresponds to a particular concern of model specification that could lead to a biased causal conclusion. Firstly, Section 4.4.1 focuses on the issue of potential exogenous policy effects, considering the occurrence of unexpected and sudden government policy decisions of a regulative nature. Unanticipated policy shocks of this kind have been shown to exert significant, asymmetric effects on key macro-financial variables more broadly (Chang et al., 2022), motivating the explicit treatment of exogenous policy events as a distinct robustness dimension in this study. Secondly, Section 4.4.2 controls for regional fixed effects to consider the influence of geographical heterogeneity. Thirdly, Section 4.4.3 checks the robustness of the empirical results using a binary response model specification for the dependent variable. Fourthly, Section 4.4.4 uses Propensity Score Matching (PSM), a method that aims to correct any resultant imbalance of the sample's observed characteristics. Finally, Section 4.4.5 exploits the quasi-experimental nature of the state-based green finance programs through the adoption of a Difference-in-Differences (DID) framework that maximizes empirical causal validity. Collectively, these robustness strategies strengthen the credibility of the empirical findings by addressing potential endogeneity, omitted variable bias, and model specification concerns.

4.5.1 Sample Adjustment

As national and international environmental statements might bring sudden changes to the degree of regulation, data after these important events were trimmed to avoid the effect of these large events on the model's estimation of the relationship between green finance and the risk of biodiversity. The re-estimated models using the trimmed sample produce largely similar coefficients. As illustrated in Table 7, Column (1), the GFI coefficient (-2.275) remains unfavorable and significant at the 5 percent level. This confirms that the conditional beneficial effect of green finance on the risk of biodiversity is not driven by important exogenous policy events but is a true structural relationship between finance and the environment. This finding reinforces the stability of the estimated relationship and mitigates concerns regarding policy-driven structural breaks.

4.5.2 Supplementary Fixed Effects

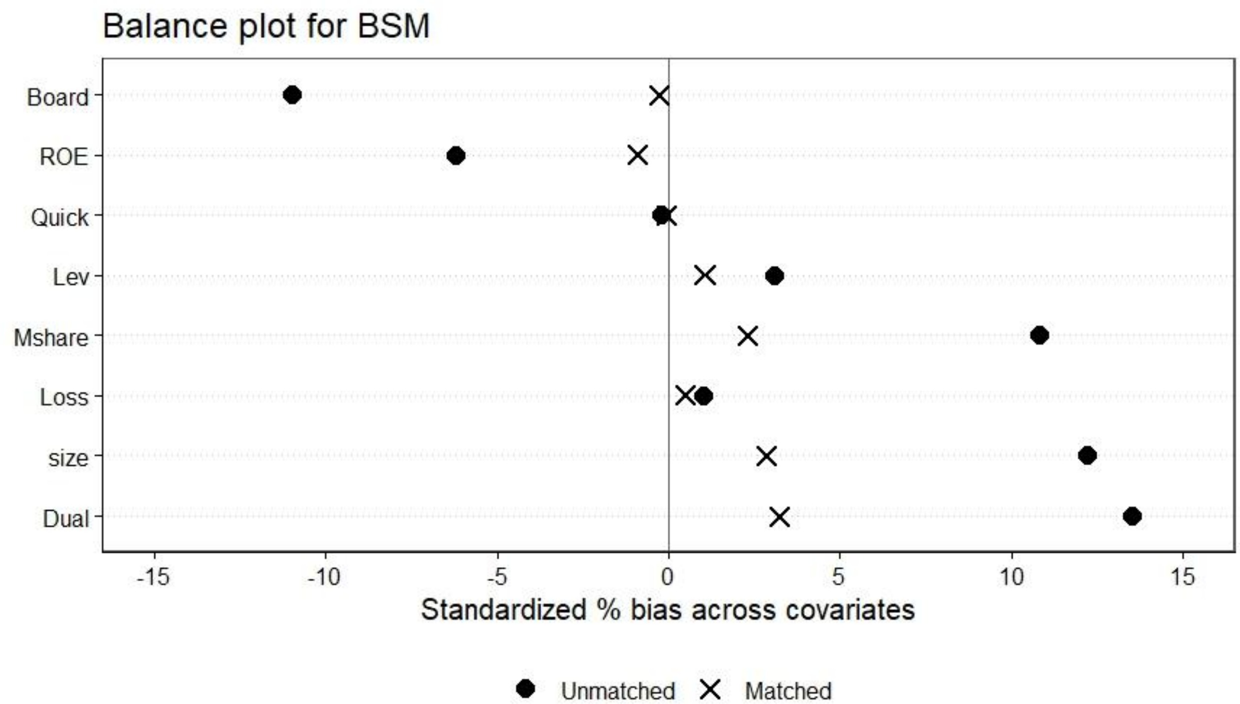
Local differences in the level of socioeconomic development, industrial structure, and natural resources could also influence the risk of biodiversity. To suppress the omitted variable problem caused by such regional heterogeneity, the regression model includes the area-fixed effects, time, and industry-fixed effects. As shown in Table 7, Column (2), the GFI coefficient significance at a 1 percent level with an unfavorable symbol remains unchanged (-7.305), and the result confirms that the basic hypothesis remains valid even after considering the unobservable regional features. This further strengthens the fact that the green finance role in mitigating the risk of biodiversity is not regional but national. This result highlights the generalizability of green finance effects across different geographic contexts.

4.5.3 Alternative Regression Specification

However, to ensure that the findings are robust to the shape of the dependent variable, the risk of biodiversity (BR) is converted into a dummy variable that equals 1 if the firms are exposed to biodiversity and 0 otherwise. Using logit regression, the GFI coefficient (–0.948) is unfavorable and substantial at 10 percent level (Column 3, Table 7). The key implication that green finance mitigates the vulnerability of firms related to biodiversity risk thus remains valid even after the specification of the dependent variable changes from continuous to categorical. This confirms that the empirical relationship is not sensitive to measurement scale or functional form of the dependent variable.

Figure 2 presents the PSM balance plot. The motivation for presenting this figure is to visually demonstrate that the matching procedure successfully balanced the treatment and control groups on observed covariates, addressing selection bias concerns.

Figure 2. PSM Balance Plot



Note: This figure displays the balance plot for Propensity Score Matching (PSM). The x-axis shows the standardized % bias across covariates, and the y-axis lists the covariates (Size, Lev, ROE, Quick, Board, Loss, Dual, Mshare). Circles represent the unmatched sample, and crosses represent the matched sample. The vertical dashed line at 5% indicates the conventional threshold for acceptable bias. After matching, all covariates show bias below 5%, indicating successful balancing between treatment (GFI ≥ median) and control (GFI < median) groups.

4.5.4 PSM (Propensity Score Matching)

These could lead to endogeneity issues related to the omission of unseen firm attributes, reverse causal relations, and omitted variables, potentially contributing to biased OLS estimation. These issues were alleviated using a Propensity Score Matching. The firms were then stratified into a control group (GFI < median) and a treatment group (GFI ≥ median), and a 1:1 match was formed using a probit model with the same set of control variables used in the baseline regression model.

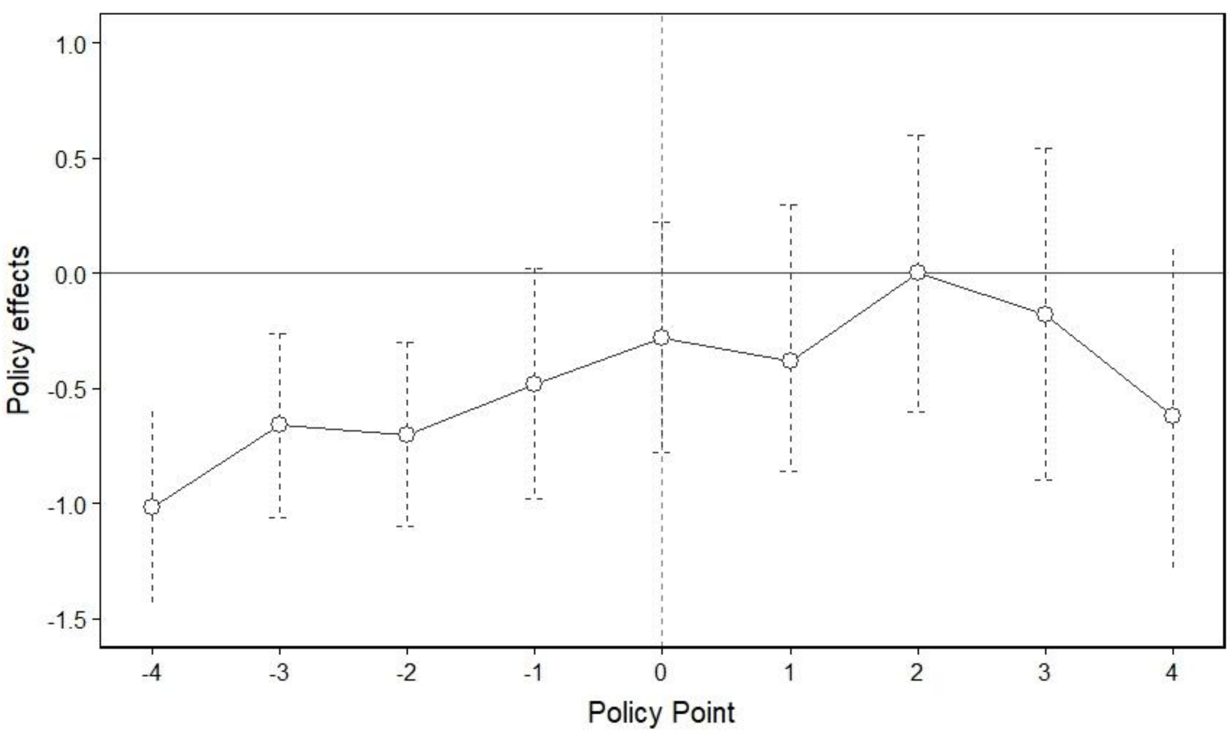
The balance plot of the PSM balance (Figure 2) illustrates that the differences between the treatment and control groups concerning the covariates are reduced significantly after the matching procedure, ensuring a high degree of comparability. The re-estimated regression analysis using the matched sample yields a GFI coefficient of -1.136, which is significant at the 5 percent level (Column 4, Table 7). This proves that even after accounting for a possible selection issue, the significant and negative influence on the corporate biodiversity risk by the green finance remains, ensuring the causal robustness of the empirical findings. This approach effectively addresses selection bias and strengthens causal interpretation of the results.

4.5.5 Exogenous Shock Assessment

To achieve enhanced causal identification, the study harnesses the power of the U.S. Green Finance Policy Initiatives (GFPIs), which launched the introduction of the green-bond schemes and environmental finance reforms at various times and within various states. The various initiatives are the perfect quasi-experiment to utilize for the analysis of the causal effect of the introduction of environmental finance. States that launched the Green Finance Policy Initiatives (GFPIs) between the years of 2012 and 2018 are considered the treatment group, and the other states that did not initiate such programs are the control group.

Figure 3 presents the parallel trends test plot. The motivation for presenting this figure is to validate the key identifying assumption of the DID approach—that treatment and control groups followed parallel trends in biodiversity risk before policy implementation.

Figure 3. Parallel Trends Test Plot



Note: This figure displays the parallel trends test for the Difference-in-Differences (DID) analysis. The x-axis shows years relative to policy implementation (t=0 is the year of GFPI adoption). The y-axis shows corporate biodiversity risk (BR). The solid line represents the treatment group (states adopting GFPIs), and the dashed line represents the control group (states without GFPIs). The vertical dashed line at t=0 marks the policy implementation year. Before t=0, both groups exhibit parallel trends with no significant differences. After t=0, the treatment group shows a significant decline in BR relative to the control group, supporting the validity of the DID approach.

Based on the endogeneity-treatment model proposed by Fuchs-Schündeln and Hassan (2016), a Difference-in-Differences (DID) approach is used to compare the treated states (states adopting GFPIs) and the untreated states. Prior to the estimation, a parallel trend test and event study of dynamics shows that the DID approach is appropriate and valid, with the parallel trend chart shown in Figure 3 illustrating that the pre-policy trend of both the control groups and treated is comparable. The regression estimate shown in Table 7's Column (5) displays a significant unfavorable DID effect (–1.652, $p < 0.01$). This outcome provides compelling evidence of the actual impact of green finance policies, thereby reinforcing their significance as effective tools for environmental policy and corporate sustainability. This quasi-experimental result provides a more robust causal inference of the study.

4.6 Moderation Analysis

Table 8 reports the moderation analysis results. Unlike the mediation analysis reported in Table 6, which examines whether corporate green development serves as a transmission channel between green finance and biodiversity risk, the moderation analysis investigates whether the effectiveness of green finance depends on external environmental conditions. Specifically, climate risk is expected to strengthen the influence of green finance on corporate green development. To evaluate this conditional relationship, an interaction term between Green Finance Index (GFI) and Climate Risk (CR) is introduced into the empirical model via Equation (8). A statistically significant interaction coefficient indicates that climate risk moderates the relationship between green finance and corporate green development, thereby providing a direct empirical test of Hypothesis 3.

Table 8. Results of mechanism assessment

Variables	**(1)**	**(2)**
	GD (GTFP)	GD (GTFP)
Green Finance Index (GFI)	0.049* (1.902)	0.011** (2.876)
Climate Risk (CR)	—	–0.003 (–1.185)
GFI × CR	—	0.023*** (3.421)
IND FE	Yes	Yes
Controls	Yes	Yes
Year FE	Yes	Yes
Observations	3836	3836
Adjusted R^2	0.017	0.046

Note: This table reports the moderation analysis associated with Hypothesis 3. Green Finance Index (GFI) significantly influences Corporate Green Development (GD), while the interaction term (GFI × CR) captures the moderating effect of Climate Risk (CR). A positive and statistically significant interaction coefficient indicates that climate risk strengthens the effectiveness of green finance in promoting corporate green development. Statistical significance is indicated by ***, **, and * for 1%, 5%, and 10% levels, respectively.

As shown in Table 8, Column (1) presents the baseline relationship between Green Finance Index (GFI) and Corporate Green Development (GD), measured by Green Total Factor Productivity (GTFP). The coefficient of GFI is positive (0.049) and statistically significant at the 10% level, indicating that green finance promotes environmentally sustainable production practices, green innovation, and resource efficiency.

Column (2) incorporates Climate Risk (CR) and the interaction term (GFI × CR). The interaction coefficient is positive and highly significant (0.023, $p < 0.01$), providing strong evidence that climate risk strengthens the positive influence of green finance on corporate green development. Although the standalone coefficient of Climate Risk is statistically insignificant, the significant interaction effect indicates that firms operating in regions exposed to greater climate-related risks derive greater sustainability benefits from green finance. These findings suggest that climate risk acts as a conditioning factor that amplifies the effectiveness of green finance in promoting environmental transformation and green productivity improvement.

Therefore, Hypothesis 3 is supported. Consistent with Guo et al. (2023), Ren et al. (2022), and Al-Qadhi et al. (2026), climate-related pressures increase firms' incentives to undertake environmental adaptation and sustainability-oriented investments. Unlike Hypothesis 2 (mediation through green development), Hypothesis 3 (moderation by climate risk) demonstrates that climate risk strengthens the positive influence of green finance on corporate green development through a significant interaction effect.

4.7 Heterogeneity Analysis

The influence of green finance on biodiversity risk management varies across different contexts. This heterogeneity is analyzed with respect to three key factors: environmental protection regulations, industry pollution intensity, and the environmental awareness of corporate executives. Table 9 provides insights into these conditional effects, offering valuable implications for policy-making.

Table 9 Heterogeneity assessment findings

Variables	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	High-level	**Low-level**	**HP**	**NHP**	**High**	**Low**
Green Finance Index	–2.548** (–2.432)	–0.138 (–0.195)	–1.482** (–2.402)	0.812 (1.041)	–1.165* (–1.821)	–0.692 (–0.884)
Year FE	YES	YES	YES	YES	YES	YES
Controls	YES	YES	YES	YES	YES	YES
IND FE	YES	YES	YES	YES	YES	YES
Observations	1350	2400	2850	870	2360	1740
Adjusted R^2	0.221	0.145	0.148	0.225	0.172	0.178

Note: This table shows heterogeneity assessment results. Green Finance Index significantly impacts Biodiversity Risk for high-level groups in models (1) and (3). Statistical significance is indicated by ***, **, and * for 1%, 5%, and 10% levels, respectively.

4.7.1 Ecological Regulations

The effectiveness of green finance policies is strongly influenced by the regulatory framework in place. Firms were classified into high and low regulation groups based on a composite measure of environmental stringency. Regression results (Columns 1 and 2 in Table 9) show that the negative impact of green finance on biodiversity risk is more pronounced in regions with stricter regulations. This suggests that stronger environmental policies not only compel firms to comply but also enhance the effectiveness of green finance, which provides the necessary resources for firms to meet regulatory standards (Yan et al., 2022).

4.7.2 Pollution Intensity

Industries with varying levels of ecological impact experience different effects from green finance. The companies were classified according to their level of emissions as either heavy polluters (HP) or nonheavy polluters (NHP). According to the regression model presented in Columns 3 and 4 of Table 9, green financing negatively influences NHP companies, but its effect on HP companies is insignificant. This is due to the fact that NHP companies are more adaptable and do not have to adhere to strict regulations, hence they can benefit greatly from green finance incentives. On the other hand, HP companies, which must undergo technological improvements, cannot gain from green financing policies immediately.

4.7.3 Executives' Green Awareness

The importance of managerial cognition is vital in determining the success of green financing. The awareness of the executives about the environmental concerns determines how companies conduct themselves and integrate sustainable practices in their activities. The study applied the Executive Green Awareness Index (Chen et al., 2024) to differentiate the level of awareness of the company's executives regarding environmental issues. The findings (Columns 5 and 6 of Table 9) show that companies with highly environmentally aware executives greatly benefit from green financing policies since the executives integrate sustainable business practices in their activities. On the other hand, companies with low environmentally aware executives are less responsive to green financing policies.

5 Conclusions and Discussion

This paper analyzed the effect of green finance on the biodiversity risk of corporations based on data collected from US-listed firms from 2003 to 2025. This paper makes a contribution to existing studies by identifying the importance of green finance in bridging the link between financial development and biodiversity risk reduction and expanding the scope of sustainable finance to include biodiversity protection instead of focusing solely on climate change issues. Findings of this paper reveal a consistent negative relationship between green finance and biodiversity risk for corporations in all models, emphasizing the importance of nature-friendly financial systems in mitigating the biodiversity risks of firms.

In addition to this, it also identifies a transmission mechanism via which biodiversity outcomes are affected by green finance. The corporate green development feature emerges as a mediating mechanism in this regard, reflecting improvements in technology innovation, resource utilization, and eco-friendly production methods. However, it must be noted that this mediating effect of green finance must be interpreted cautiously, as indicated by the relatively low explanatory power of the first-stage model. This suggests that biodiversity risk reduction might also be achieved via other mechanisms, including regulatory pressures and influence from stakeholders and supply chains. Moreover, it is also observed that the effectiveness of green finance is enhanced in the context of elevated climate risk. This moderating effect is informed by the theoretical constructs of adaptive pressures and risk perceptions, in which firms tend to be more responsive to financial incentives promoting sustainability in the context of elevated climate risk. Thus, the climate and biodiversity risk are incorporated into a single framework of analysis, providing a more comprehensive perspective on financial dynamics in the environment.

The results further show that there is significant heterogeneity with respect to different institutional or organizational settings. For instance, the effectiveness of green finance is found to be greater in regions with stringent environmental regulations, sectors with fewer transition constraints, and firms with better environmental corporate governance. However, it is essential to note that while interpreting heterogeneous results, it is vital to consider the classification of different groups, for example, high or low regulations, where the results are based on certain threshold values. In future studies, it is recommended to improve the classification results to achieve greater robustness. Overall, the results show that the effectiveness of green finance is not absolute, considering the broader context. Therefore, the research contributes to the literature by highlighting the context-specific nature of the relationship between finance and the environment, while providing new research insights on the role of institutions from the perspective of biodiversity.

However, the research is not without a few limitations. Firstly, the measurement of corporate-level biodiversity risk is conducted through a sentiment analysis of the 10-K reports. Although this provides a more transparent approach and is in line with the TNFD framework, this might not accurately reflect the material risk exposure for biodiversity. Moreover, there might be a measurement bias involved. Although the biodiversity proxy is aligned with the TNFD categories of dependencies, impacts, risks, and opportunities, further integration of these categories would be useful for a more precise measurement. The dataset extends up to 2025, with the incorporation of the latest available disclosures and preliminary datasets. Although the robustness of the results is established, the incorporation of recent data might be a cause for concern. It should be used with caution. In future research, this limitation could be overcome through the incorporation of more objective environmental indicators. Satellite imagery for biodiversity, pollution, and ecosystem-level indicators would be useful. In addition, further research could be conducted in a cross-country context with the incorporation of more transmission channels.

From a policy point of view, there are significant implications that can be derived from the results obtained in this paper. Governments need to enhance and expand green finance instruments such as green bonds, sustainability-linked loans, and biodiversity funds in order to channel more funds towards environmental conservation. However, the attenuation of green finance effects in this paper suggests that there is a need to look into other factors that significantly impact green finance outcomes. As a result, it is not enough to focus on green finance instruments; there is also a need to look into other factors that impact green finance outcomes, including institutional factors and structural factors. There is a need to enhance standardization and transparency in biodiversity disclosures, including TNFD.

At the corporate level, it is encouraged that biodiversity and climate change risk assessment results are incorporated into the firm's strategic planning and ESG reporting processes. This way, the obligations related to sustainability and environmental issues are converted into opportunities for innovative and competitive success. Moreover, the role of investors is also important in the process, where they are encouraged to include biodiversity-related risks in the process of portfolio allocation. Thus, the market forces are further encouraged to contribute to sustainability. However, further research is required to improve the methodologies and models in the process of measuring the results. It is concluded that the present study highlights the importance of green finance in the process of linking the development of finance and the sustainability of biodiversity. The present study not only contributes to the academic literature but is also a good starting point for further research in the process of nature-related financial risk management.

Funding Acknowledgment: The author extends his appreciation to Prince Sattam bin Abdulaziz University for funding this research work through the project number (PSAU/2025/02/37136)

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