Biodiversity physical and transition risk: the relationship with firm financial performance

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Abstract

Across 24753 firm year observations, we investigate the relationship of firms' financial performance with biodiversity physical and transition risk from 2000 to 2023. Using dependency rating and pressure rating from Encore as poxy for physical risk and transition risk respectively. The results show that the negative relationship between biodiversity risk and financial performance is more pronounced for firms with high pressure rating, through higher production costs and stakeholder engagement. By categorizing biodiversity dependency into three ecosystem services group, we find negative nexus between biodiversity risk and financial performance strengthens for firm with high dependency rating on regulating and maintenance ecosystem services. Our findings are consistent across several robustness tests. Overall, our study shed light on the relationship of firms' financial performance with biodiversity physical and transition risk.

Keywords: biodiversity, risk, dependencies, pressures, financial performance, natural capital

JEL: G35, Q51, Q57

1. Introduction

Biodiversity is under significant threat from human activities such as habitat destruction, pollution, overexploitation of resources and spread of invasive species. As biodiversity loss comes after climate change as another major global concerns, businesses that either dependent on ecosystem service provided by nature or imposing pressure on nature are facing increasing level of risks. These risks, refer to as biodiversity risk, can be manifested in two forms: First, physical risk for firms that are dependent on ecosystem services, this risk emerges from the disruption of ecosystem services which will lead to operational

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instability, higher costs or even the loss of business; Second, transition risk for firms that are putting pressure on nature, this risk comes from change of regulation, investor's preference and social expectation when economies are in transition to be more sustainable. These potential risks are likely to materialize as real risks if not taken care of properly. According to World Economic Forum, biodiversity loss was identified as one the top five risks for global economy, and half of global GDP was estimated either moderately or highly dependent on nature and ecosystem services it provides (World Economic Forum, 2020; World Economic Forum & PwC, 2020). According to Central Banks and Supervisors Network for Greening the Financial System, biodiversity risk is estimated to be systemic risk in the coming years (NGFS, 2021). In December of 2022, the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted at COP15[2], this landmark agreement set out global initiative to halt and reverse biodiversity loss. One year later, TNFD[3] is officially published, this disclosure framework enables business and financial institutions with the tools to assess, manage and disclose nature related financial risks. Therefore, It also serves as complementary to the Kunming-Montreal Global Biodiversity Framework. As such, it is important to know if there is any implication of biodiversity risk on business currently and what's the channel for this implication to happen.

This research is mainly to investigate: "What is the relationship of firms' financial performance with biodiversity physical and transition risk." The mechanisms of biodiversity loss impacting on operation of business are supported by several theories: Resource-based view theory (Barney, 1991) suggests that firms build competitive advantage through rare, valuable and non-substitutable resources. The biodiversity degradation reduces firm's ability to access valuable resources, therefore increasing costs and impairing profitability; Stakeholder theory (Freeman, 1984) advocates considering the interests of all parties that are involved in or impacted by the business, challenging shareholder theory for taking maximizing shareholder value as the sole responsibility. Stakeholders include regulators, investors and consumers, companies that fail to manage business' pressure on biodiversity might face reputation damage and

[2] 15th Conference of the Parties to the UN Convention on Biological Diversity
[3] Taskforce on Nature-related Financial Disclosures (TNFD) Recommendations

regulatory punishments imposed by stakeholders, causing reduced investor's confidence and profitability.

The contribution of this research is multifold: First, in prior research, the proxy of biodiversity risk is limited to self-reporting biodiversity word count (Bach et al., 2025). In our study, we not only replace simple word count with sentiment sentences ratio as proxy for general biodiversity risk, but we also further leverage on Encore dependency rating and pressure rating to examine the impact of biodiversity physical risk and transition risk separately. This enables us to assess biodiversity risk impact in the lens of double materiality standard, therefore making it possible to examine biodiversity risk financial performance nexus in more granularity and precision.

Second, this research utilizes biodiversity dependency and pressure rating sourced from Encore and merges it with biodiversity risk dataset developed by Giglio et al. (2023) and firms' financial data sourced from LESG Workspace. This combination has not been seen in prior research.

Third, it is the practical implication of this research: On policy maker side, this research explicitly examines the effect of transition risk on financial performance, providing policy maker with the better understanding of this nexus. It can also justify implementation of stricter environmental regulation and policy for biodiversity conservation. In addition, the contribution of this research provides evidence for further enhance of existing farmwork, such as TNFD, to better integrate biodiversity consideration into firm's disclosure; For investors, this research can provide them the more explicit link between biodiversity risk and financial performance, enabling them to make more informed investment decision by taking biodiversity impact into consideration.

The remainder of this research is organized as follows. Section 2 is the literature review and research development; Section 3 introduces the data and methodology; Section 4 presents the results; Section 5 is the discussion and conclusion.

2. Literature review and research development

The nexus of environmental risk and firm's performance has been discussed for a long period of time before biodiversity concerns were put under the spotlight. One of the best

representations is the research on climate change risk. For instance, climate risk is found to have financial implications on firms and particularly related regulatory risk has started to materialize (Krueger et al., 2020). One of the mechanisms in work is that investors have priced in climate risk as evidence shows that there is positive relationship between carbon emissions and stock risk premium (Bolton & Kacperczyk, 2021). The implications are not only confined to stock market, because climate change risk is also found being associated with the pricing of long-term municipal bonds (Painter, 2020) and futures market expectation (Schlenker & Taylor, 2021). While climate is being regularly discussed in mainstream finance journals, biodiversity loss emerges as second global environmental issues after climate change according to the Global Risk Report issued by World Economic Forum (World Economic Forum, 2025). The resultant biodiversity risk topic is still niche field in finance research but gaining huge momentum in recent years. It starts with a call for biodiversity finance research by Karolyi and Tobin-de la Puente (2023), where they layout framework for research on biodiversity loss related risk with the aim to closing financing gap for biodiversity conservation. In the same vein, Flammer et al. (2025) feature their research by analyzing deal-level data back by ongoing biodiversity conservation project, the research highlights favorable risk-return profile provided by blended financing are more attractive to private capital, and unlikely private capital alone is able to substitute public financing in terms of biodiversity conservation. In finance literature, one of the first attempt at assessing biodiversity risk is conducted by Giglio et al. (2023), in their research, biodiversity risk exposure is compiled on textual analysis of 10-K reports of all US listed firms, additional measures include news-based measure and a large survey for concerned parties. These measures are then widely adopted in subsequent biodiversity finance research (Liu et al., 2025; Chen et al., 2025; Zhou et al., 2025; Bach et al., 2025; Li et al., 2025; El Ouadghiri et al., 2025). The results generally show that biodiversity risk has already interacted with wide range of corporate behaviors including but not limited to dividend payout (Zhou et al., 2025), seasoned equity offering (Liu et al., 2025) and management myopia (Zhao et al., 2025).

There are also few discussions specifically on the relationship of biodiversity risk and financial performance. Leveraging on proprietary biodiversity footprint data provided by Iceberg Data Lab, Garel et al. (2024) are able to conduct an event study on stock return

time series and find that investors started to ask biodiversity premium after some significant biodiversity events. Instead of looking at real time market pricing, Bach et al. (2025) investigate biodiversity risk impact on firm's financial performance, and negative impact is found for US listed firms. Building on these findings, we further advance the analysis through the lens of double materiality, specifically examining the relationship of biodiversity physical risk and transition risk with financial performance. Therefore, we propose the first hypothesis:

H1: Biodiversity physical and transition risk are negatively related with firm's financial performance

Backed by resource-based view theory, the potential profitability loss comes from higher costs incurred by losing access to strategic resources (Barney, 1991). This is worth to study as a channel for reduction in firm's profitability due to biodiversity loss. While stakeholder theory states another channel that firm's profitability is inflicted by reputation damage and regulatory punishment. In response to downside risk from stakeholder pressure, firms may be more likely to communicate with public about their initiative on biodiversity conservation. Therefore, we may see more likely firms disclose they have biodiversity impact reduction policy if they in practice put high pressure on biodiversity conservation. As such, it gives us opportunity to explore through which channel financial performance takes negative effect from biodiversity physical and transition risk. We propose the second hypothesis:

H2: The negative relationship of biodiversity physical and transition risk with financial performance is channeled through high production cost and high stakeholder engagement

We contribute to current discussion on biodiversity finance by presenting the first empirical analysis on the relationship between biodiversity physical & transition risk and firm's financial performance. And in addition, we explore the through which channel these risks impact on financial performance.

3. Research design

3.1 Data

3.1.1 Biodiversity risk exposure and firm financial data

This study examines US publicly listed companies over the period from 2000 to 2023. Financial and firm-specific data are sourced from LESG Workspace, firm level biodiversity risk is proxied by biodiversity negative score following the methodology of Giglio et al. (2023). This score is a reflection of firm's negative sentiment towards biodiversity exposure, it is a better gauge for the biodiversity risk that companies are facing. Companies in the financial and utility sectors are excluded from the analysis. Continuous variables are winsorized at the 1st and 99th percentiles to mitigate the impact of outliers. The final dataset comprises of 24,753 firm-year observations.

3.1.2 Biodiversity dependency and pressure rating from ENCORE

ENCORE, which stands for *Exploring Natural Capital Opportunities, Risks, and Exposure*, was first developed in 2018 through a collaboration between Global Canopy, UNEP FI, and UNEP-WCMC. This database is designed to identify nature-related risks and provide insights for organizations to better understand their dependencies on ecosystem services and pressures exerted on nature. The industry-level ecosystem dependency score is rated into five levels: Very High (VH), High (H), Medium (M), Low (L), and Very Low (VL). These ratings correspond to quantitative materiality scores ranging from 2 to 6, with higher scores indicating a greater dependency on ecosystem services (ES). Similarly, the industry-level pressure materiality score uses the same rating scale, from VL to VH. The pressure score is calculated with a weighted approach, assigning three times more weight to the magnitude of the pressure compared to the scale of economic activity. The absolute scores for each rating range from 4 to 12, with higher scores indicating more significant environmental pressures. Table 1 demonstrates the ecosystem service types and pressure types.

Table 1

Ecosystem services and pressures

Ecosystem services	Pressures
Provisioning services: Biomass provisioning services; Genetic material services; Water supply; Other provisioning services – Animal-based energy **Regulating and maintenance services**: Global climate regulation services; Rainfall pattern regulation services; Local (micro and meso) climate regulation services; Air filtration services; Soil quality regulation services; Soil and sediment retention services; Solid waste remediation; Water purification services; Water flow regulation services; Flood mitigation services; Storm mitigation services; Noise attenuation services; Pollination services; Biological control services; Nursery population and habitat maintenance services; Other regulating and maintenance service – Dilution by atmosphere and ecosystem; Other regulating and maintenance service – Mediation of sensory impacts **Cultural services**: Recreation-related services; Visual amenity services; Education, scientific and research services; Spiritual, artistic and symbolic services	Emission of GHGs Emission of non-GHG air pollutants Other biotic resource extraction (e.g. fish, timber) Other abiotic resource extraction Generation and release of solid waste Area of land use Volume of water use Disturbances (e.g. noise, light) Area of freshwater use Area of seabed use Emissions of toxic pollutants to water and soil Emissions of nutrient pollutants to water and soil Introduction of invasive species

Source: Expanatory note on the updated ENCORE knowledge base outlining business dependencies and impacts on nature, UNEP-WCMC, June 2024

3.2 Methodology

Using panel data regression model, firstly we examine the relationship of financial performance with general biodiversity risk proxied by negative score. Afterwards, we integrate dependency and pressure rating in the model, examining the effect of biodiversity physical risk and transition risk on financial performance. The baseline regression models are shown as follows:

$$ROA_{i,t} = \beta_0 + \alpha_1 BiodiversityRisk_{it} + \alpha_2 Cintrol_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (1)$$

$$ROA_{i,t} = \beta_0 + \alpha_1 (BiodiversityRisk_{it} * HighDependencyDummy_{it}) + \alpha_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (2)$$

$$ROA_{i,t} = \beta_0 + \alpha_1 (BiodiversityRisk_{it} * HighPressureDummy_{it}) + \alpha_2 Control_{it} + \mu_i + \delta_t + \varepsilon_{it} \quad (3)$$

Where the dependent variable is the financial performance of firm i in year t, which is proxied by return on asset (ROA). Biodiversity risk measure follows methodology of Giglio et al. (2023), it is proxied by negative score. Biodiversity dependency and pressure rating are sourced from ENCORE database: High dependency dummy is assigned 1 if companies are with high and very high dependency rating, 0 otherwise; The same applies to high pressure dummy. $Control_{it}$ are control variables. More specifically, the selection of control variables follows the prior literatures (Titman & Wessels, 1988; Rajan & Zingales, 1995; Becker et al., 1998; Opler et al., 1999; Bhagat et al., 2008), it includes firm size (*SIZE*), Leverage (*LEV*), Tangibility (*TAN*), Book to market ratio (*BM*), Operating cash flow (*CF*), Cash and cash equivalent (*CCE*) and Big 4 auditing dummy (*Big_4*). μ_i is firm fixed effect, δ_t is year fixed effect. The detailed description of independent variables, control variables and interaction terms can be found in Appendix A.

4. Results

4.1 Baseline regression

Table 4 shows the baseline regression results of relationship between biodiversity risk and financial performance based on full sample. The significant negative relationship between financial performance and biodiversity risk is found in all four model specifications. After controlling for firm fixed effect and year fixed effect, one standard deviation increasing in biodiversity risk reduces return on asset by 0.06%. The magnitude of coefficients for biodiversity risk don't have much deviation across all four regression models. This negative relationship is in line with expectation that accelerating biodiversity loss is being transformed to the cost for firms' business, therefore weakening the profitability measure. In the next baseline regression, we integrate Encore dependency and pressure rating in order to further dissect biodiversity risk and find out the relationship of biodiversity physical risk and transition risk with firm's financial performance.

Table 5 shows the results, the coefficient of interaction term between high biodiversity pressure dummy and biodiversity risk is negative and significant at 10 % level. The indication is that the negative relationship between biodiversity risk and financial performance is more pronounced for firms from high pressure industries, return on asset is reduced by 0.8% more compared to firms outside high pressure industries. However, this is not the case for firms from high dependency industries, no significant difference is found for firms within high dependency industries compared to the firms outside, the magnitude of coefficient is also extremely close to zero. The explanation of this outcome is that companies' dependency rating represents physical risks for companies, pressure rating represents transition risk. However, typically physical risk takes much longer time to realize in comparison to transition risk, therefore the profitability reduction effect has not yet appeared for companies that operate in high biodiversity dependency industries.

Table 2
Descriptive statistics

	Obs	Mean	SD	Min	Max
ROA	35785	0.018	0.154	-0.741	0.265
BRE_N	47261	0.014	0.209	-6.000	5.000
SIZE	40800	20.907	1.728	17.061	25.412
LEV	40579	0.528	0.265	0.051	1.336
BM	28234	0.464	0.455	-0.309	2.803
TAN	38381	0.377	0.232	0.013	0.942
CF	40649	0.060	0.148	-0.614	0.348
CCE	40605	0.147	0.168	0.001	0.833
BIG_4	47261	0.736	0.441	0.000	1.000

Notes: All continuous variables are winsorized at the 1st and 99th percentiles. Obs, Mean, SD, Min, and Max stand for number of observations, average value, standard deviation, minimum value and maximum value respectively

Table 3
Correlation table

	ROA	BRE_N	SIZE	LEV	BM	TAN	CF	CCE	BIG_4
ROA	1.00								
BRE_N	0.02*	1.00							
SIZE	0.34***	0.03***	1.00						
LEV	0.07***	-0.01*	0.40***	1.00					
BM	-0.04***	0.07***	0.03***	-0.19***	1.00				
TAN	0.21***	0.13***	0.33***	0.26***	0.14***	1.00			
CF	0.87***	0.04***	0.31***	0.09***	-0.05***	0.28***	1.00		
CCE	-0.38***	-0.05***	-0.41***	-0.28***	-0.16***	-0.46***	-0.34***	1.00	
BIG_4	0.03***	-0.00	0.30***	0.15***	-0.03***	0.04***	0.04***	-0.10***	1.00

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively.*

Table 4
The effect of biodiversity risk on firm financial performance

VARIABLES	(1) ROA	(2) ROA	(3) ROA	(4) ROA
BRE_N	-0.007**	-0.007***	-0.007**	-0.006***
	(0.003)	(0.002)	(0.003)	(0.002)
SIZE	0.008***	0.020***	0.008***	0.019***
	(0.001)	(0.001)	(0.001)	(0.002)
LEV	-0.033***	-0.071***	-0.033***	-0.071***
	(0.004)	(0.006)	(0.004)	(0.006)
TAN	-0.066***	-0.037***	-0.066***	-0.033***
	(0.004)	(0.008)	(0.004)	(0.008)
BM	-0.007***	-0.028***	-0.006***	-0.028***
	(0.002)	(0.002)	(0.002)	(0.002)
CF	0.889***	0.652***	0.894***	0.657***
	(0.010)	(0.017)	(0.010)	(0.017)
CCE	-0.119***	-0.050***	-0.119***	-0.044***
	(0.007)	(0.008)	(0.007)	(0.008)
BIG_4	-0.012***	-0.005	-0.010***	-0.005
	(0.003)	(0.004)	(0.003)	(0.004)
Constant	-0.135***	-0.364***	-0.128***	-0.344***
	(0.012)	(0.023)	(0.012)	(0.035)
Observations	24,753	24,753	24,753	24,753
R-squared	0.787	0.506	0.790	0.516
Firm FE	NO	YES	NO	YES
Year FE	NO	NO	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of all variables can be found in Appendix A*

Table 5
The effect of biodiversity physical risk and transition risk on financial performance

VARIABLES	(1) ROA	(2) ROA
HD * BRE_N	0.000	
	(0.007)	
HP * BRE_N		-0.008*
		(0.004)
BRE_N	-0.006***	0.001
	(0.002)	(0.003)
SIZE	0.019***	0.019***
	(0.002)	(0.002)
LEV	-0.071***	-0.071***
	(0.006)	(0.006)
TAN	-0.033***	-0.033***
	(0.008)	(0.008)
BM	-0.028***	-0.028***
	(0.002)	(0.002)
CF	0.657***	0.657***
	(0.017)	(0.017)
CCE	-0.044***	-0.044***
	(0.008)	(0.008)
BIG_4	-0.005	-0.005
	(0.004)	(0.004)
Constant	-0.344***	-0.344***
	(0.035)	(0.035)
Observations	24,753	24,753
R-squared	0.516	0.516
Firm FE	YES	YES
Year FE	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of all variables can be found in Appendix A*

Overall, there is no significant effect on financial performance found for biodiversity physical risk. According to SEEA EA[4] report (United Nations, 2021), ecosystem services

[4] System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA EA)

can be categorized into three groups: Provisioning services, Regulating and maintenance services and Cultural services. Each type of service provides companies with access to different functionalities, for example, water supply is in provisioning services, pollination is in regulating and maintenance service, recreation-related service falls within the scope of cultural services. To dissect the impact of biodiversity physical risk, we take dependency rating for these three ecosystem services and interact with biodiversity risk separately. The result demonstrates that companies with exposure to regulating and maintenance services experience more reduction in profitability when biodiversity risk is presented, it is significant at 10% level. The effect of provisioning services exposure is negative as well, but this result is not statistically significant. The opposite effect is shown in cultural services, but it is not convincing due to statistically and economically insignificance. The regression results are shown in table 6.

Table 6
The effect of biodiversity dependency sub-group on financial performance

VARIABLES	(1) ROA	(2) ROA	(3) ROA
HPROV * BRE_N	-0.008		
	(0.006)		
HREG * BRE_N		-0.014*	
		(0.008)	
HCUL * BRE_N			0.010
			(0.007)
BRE_N	-0.002	-0.002	-0.005*
	(0.002)	(0.002)	(0.003)
SIZE	0.026***	0.026***	0.026***
	(0.002)	(0.002)	(0.002)
LEV	-0.069***	-0.069***	-0.069***
	(0.007)	(0.007)	(0.007)
TAN	-0.015	-0.015	-0.015
	(0.011)	(0.011)	(0.011)
BM	-0.024***	-0.024***	-0.024***
	(0.003)	(0.003)	(0.003)
CF	0.646***	0.647***	0.646***
	(0.020)	(0.020)	(0.020)
CCE	-0.033***	-0.033***	-0.033***
	(0.011)	(0.011)	(0.011)
BIG_4	-0.001	-0.001	-0.001
	(0.006)	(0.006)	(0.006)
Constant	-0.514***	-0.513***	-0.514***
	(0.048)	(0.048)	(0.048)
Observations	13,520	13,520	13,520
R-squared	0.550	0.550	0.550
Firm FE	YES	YES	YES
Year FE	YES	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. HPROV is 1 if companies have high or very high provisioning ecosystem service dependency rating, 0 the otherwise; HREG is 1 if companies have high or very high regulating and maintenance ecosystem services dependency rating, 0 the otherwise; HCUL is 1 if companies have high or very high cultural ecosystem services dependency rating, 0 the otherwise; The definition of all variables can be found in Appendix A*

4.2 Mechanism analysis

In this section, we dive deeper and explore how does biodiversity physical and transition risk impact on financial performance. We examine the two mechanisms: First is biodiversity impact reduction policy, representing for stakeholder engagement channel; Second is cost of goods sold, representing for production cost channel.

Table 7
Mechanism analysis: biodiversity impact reduction policy

VARIABLES	(1) IRP	(2) IRP
HD	-0.014	
	(0.177)	
HP		1.222***
		(0.161)
SIZE	0.754***	0.731***
	(0.057)	(0.057)
LEV	-0.774**	-0.375
	(0.318)	(0.320)
TAN	2.511***	2.185***
	(0.350)	(0.326)
BM	0.104	0.003
	(0.152)	(0.154)
CF	2.014***	2.115***
	(0.666)	(0.686)
CCE	0.154	0.015
	(0.664)	(0.717)
BIG_4	0.007	0.019
	(0.267)	(0.249)
Constant	-22.041***	-22.192***
	(1.276)	(1.294)
Observations	15,820	15,820
Pseudo R2	0.234	0.273
Year FE	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of variables can be found in Appendix A*

Table 8
Mechanism analysis: cost of goods sold

	(1)	(2)
VARIABLES	COGS	COGS
HD	-0.232***	
	(0.022)	
HP		0.060***
		(0.022)
SIZE	-0.081***	-0.079***
	(0.007)	(0.007)
LEV	0.088***	0.095***
	(0.019)	(0.019)
TAN	-0.226***	-0.232***
	(0.035)	(0.035)
BM	-0.022***	-0.022***
	(0.008)	(0.008)
CF	0.395***	0.410***
	(0.028)	(0.028)
CCE	-0.267***	-0.275***
	(0.021)	(0.021)
BIG_4	-0.004	-0.006
	(0.021)	(0.021)
Constant	2.359***	2.244***
	(0.145)	(0.144)
Observations	13,858	13,858
R-squared	0.06	0.03
Year FE	YES	YES

*,**and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of variables can be found in Appendix A*

Two theories that are discussed in previous chapter back the selection of channels: First, stakeholder theory states that firms with pressure on biodiversity have motivation to reduce reputational risk in order to avoid punishment from consumers. In this sense, firms with high biodiversity pressure rating are more motivated to claim they have biodiversity impact reduction policy than the otherwise, however the actual implementation of the policy is in question, therefore reporting biodiversity impact reduction policy doesn't necessarily lead to better financial performance, but it does reflect that firms are trying to mitigate reputational risk to avoid consequences stated by stakeholder theory. As such, Table 7 examines the relationship of high biodiversity dependency and high biodiversity pressure with reporting biodiversity impact reduction policy. Logistic regression is applied for this analysis, the results show that firms in high pressure industries are 3.39 times more likely to report biodiversity impact reduction policy than the others. There is no significant result found for firms in high dependency industries.

Resource view theory states that firm's profitability is harmed by increasing cost of production due to less accessibility to the necessary resources. Table 8 examines this channel by manifesting the relationship between the cost of goods sold and high biodiversity dependency and pressure. The results show that firms in high biodiversity dependency industry are likely to have lower costs, while firms in high biodiversity pressure industry are likely to have higher production costs.

Here are interpretations of mechanism analysis result: High pressure rating as poxy for biodiversity transition risk, are positively related with two mechanisms, this suggests firms with exposure to transition risk are facing imminent pressure from regulators and customers as real cost can be incurred in relatively shorter horizon; High dependency rating as proxy for biodiversity physical risk, is less visible for public due to little understanding of how does dependency matters for companies' long term operating. In addition, physical risk itself also takes long and gradual process to erode firm's profitability. Therefore, we see these two mechanisms work for transition risk but not physical risk.

4.3 Robustness Test

In our analysis, it could involve statistical errors including but not limited to selection bias, measurement bias and endogeneity. Therefore in this section, several robustness tests are conducted.

4.3.1 Propensity score matching and entropy balancing test

Table 9
Propensity score matching test statistics

Variables	Treatment	Control	Difference	P value
Panel A: Pre-matching balancing test				
SIZE	21.346	20.779	-0.567	0.000
LEV	0.506	0.534	0.028	0.000
TAN	0.428	0.361	-0.067	0.000
BM	0.512	0.441	-0.071	0.000
CF	0.078	0.054	-0.024	0.000
CCE	0.127	0.153	0.026	0.000
BIG_4	0.760	0.723	-0.030	0.000
Panel B: After-matching balancing test				
SIZE	21.487	21.371	-0.116	0.000
LEV	0.511	0.516	0.005	0.223
TAN	0.419	0.398	-0.021	0.000
BM	0.500	0.476	-0.025	0.001
CF	0.081	0.076	-0.005	0.011
CCE	0.127	0.137	0.010	0.000
BIG_4	0.873	0.867	-0.006	0.298

Note: Treatment group is those observations with high pressure dummy (HP) as 1, control group is those with high pressure dummy (HP) as 0

Table 10

Entropy balancing test statistics

	Treatment			Control		
	Mean	Variance	Skewness	Mean	Variance	Skewness
Panel A: Pre Entropy Balancing						
SIZE	21.35	3.279	0.090	21.04	2.754	0.294
LEV	0.504	0.055	0.414	0.535	0.070	0.464
TAN	0.424	0.053	0.537	0.362	0.048	0.657
BM	0.509	0.197	2.225	0.429	0.202	2.491
CF	0.079	0.014	-2.217	0.060	0.025	-1.958
CCE	0.128	0.019	2.229	0.158	0.031	1.939
BIG_4	0.858	0.122	-2.053	0.868	0.114	-2.177
Panel B: Post Entropy Balancing						
SIZE	21.35	3.279	0.090	21.34	2.905	0.280
LEV	0.504	0.055	0.414	0.504	0.056	0.288
TAN	0.424	0.053	0.537	0.424	0.055	0.430
BM	0.509	0.197	2.225	0.508	0.252	2.439
CF	0.079	0.014	-2.217	0.078	0.017	-2.086
CCE	0.128	0.019	2.229	0.129	0.022	2.300
BIG_4	0.858	0.122	-2.053	0.858	0.122	-2.054

Note: Treatment group is those observations with high pressure dummy (HP) as 1, control group is those with high pressure dummy (HP) as 0

Propensity score matching is conducted to detect potential selection bias. For this purpose, we set dummy variable based on industries. The dummy variable is assigned by 1 if it is in high biodiversity pressure industry, otherwise dummy variable is assigned by 0. As seen in table 9, the variation between control and treatment group significantly improves after matching. We then re-estimate the baseline regression with the matching sample, the negative relationship between biodiversity risk and financial performance still holds at 1% significance level, this demonstrates that the effect is not the cause of selection bias, our baseline findings are further supported.

Propensity score matching is running with exact matching, which reduces sample size significantly. In order to retain the sample size, entropy balancing is applied. The treatment group and control group are still defined by high pressure industry dummy. Table 10 shows the improvement for deviation of covariates between treatment group and control group after entropy balancing. Then we re-estimate baseline regression with entropy balancing sample, the negative relationship still holds at high significance level, which further supports our findings. The regression results after propensity matching and entropy balancing are shown in Table 11.

Table 11

Re-estimate baseline regression after propensity score matching and entropy balancing

Propensity scoring matching and entropy score matching regression result		
	Propensity Score Matching	Entropy Balancing Method
VARIABLES	ROA	ROA
BRE_N	-0.006***	-0.006***
	(0.002)	(0.002)
SIZE	0.013***	0.017***
	(0.002)	(0.002)
LEV	-0.066***	-0.068***
	(0.009)	(0.008)
TAN	-0.039***	-0.035***
	(0.010)	(0.008)
BM	-0.029***	-0.030***
	(0.003)	(0.003)
CF	0.591***	0.617***
	(0.024)	(0.018)
CCE	-0.054***	-0.049***
	(0.012)	(0.009)
BIG_4	-0.009**	-0.006*
	(0.004)	(0.004)
Constant	-0.213***	-0.301***
	(0.047)	(0.040)
Observations	12,976	24538
R-squared	0.851	0.847
Weighted with PSM	Yes	NO
Firm FE	Yes	Yes
Year FE	Yes	Yes
Clustered SEs	Yes	Yes
Weighted with EPM	NO	Yes

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of variables can be found in Appendix A*

4.3.2 Replace dependent and independent variables

Table 12
Robustness test: replace dependent and independent variable

VARIABLES	(1) ROE	(2) ROA	(3) ROA
BRE_N	-0.050**		
	(0.021)		
BRE		-0.009***	
		(0.003)	
BRE_R			-0.013***
			(0.005)
SIZE	0.044***	0.019***	0.019***
	(0.011)	(0.002)	(0.002)
LEV	-0.037	-0.071***	-0.071***
	(0.061)	(0.006)	(0.006)
TAN	-0.055	-0.033***	-0.033***
	(0.044)	(0.008)	(0.008)
BM	-0.077***	-0.029***	-0.028***
	(0.013)	(0.002)	(0.002)
CF	1.002***	0.657***	0.657***
	(0.080)	(0.017)	(0.017)
CCE	-0.071	-0.043***	-0.043***
	(0.055)	(0.008)	(0.008)
BIG_4	-0.014	-0.005	-0.005
	(0.019)	(0.004)	(0.004)
Constant	-0.790***	-0.343***	-0.342***
	(0.214)	(0.035)	(0.035)
Observations	24,752	24,753	24,753
R-squared	0.044	0.516	0.516
Industry FE	YES	YES	YES
Year FE	YES	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. The definition of variables can be found in Appendix A*

Robustness test is conducted by replacing return on asset with return on equity. The negative relationship still holds, the coefficient is significant at 5% level. Furthermore, two other biodiversity risk measurements are computed with Giglio's methodology (Giglio et al., 2023), they are biodiversity count score and biodiversity regulation count score. We

replace original biodiversity negative score with these two risk exposure measurements, biodiversity risk is still negatively related to financial performance, both are significant at 1% level. The regression results can be found in table 12.

4.3.3 Instrument variable

There is endogeneity concern that the biodiversity risk exposure is the result of financial performance. It may argue that firms deliver better financial performance through the expansion of business which could make firms more exposed to the biodiversity risks. In order to counter this concern about reverse causality, we implement instrumental variable technique. Following Safiullah et al. (2021), the geographical location is chosen as the instrumental variable. Two main reasons for this selection: First, geographical location information is reflected in US firms' three-digit zip code, zip code is exogenous to firm financial performance as this code is assigned for the convenience of postal delivery and has nothing to do with this firm's performance; Second, evidence shows that firm's Corporate Social Responsibility (CSR) level is influenced by the CSR level of surrounding firms in the same three-digit zip code (Jiraporn et al., 2014). Therefore, geographical location as instrumental variable for a firm is proxied by the average biodiversity risk of other surrounding firms in the same three-digit zip code. The two stages least square regression results are shown in table 13: In the first stage, instrumental variable is positively correlated with biodiversity risk and the coefficient is significant at 1% level; In the second stage, the biodiversity risk estimated in the first stage is used to predict financial performance, its interaction term with high pressure dummy is inversely correlated with financial performance and the coefficient is significant at 1% level. These results further support the finding that biodiversity transition risk would further reduce firm's financial performance.

Table 13
Robustness test: Instrument variables

	(1) First stage	(2) Second stage
CITY	0.103***	
	(0.0152)	
HP * BRE_N		-0.0659***
		(0.0199)
SIZE	-0.000633	0.00755***
	(0.00126)	(0.000399)
LEV	-0.0379***	-0.0331***
	(0.00763)	(0.00319)
TAN	0.158***	-0.0591***
	(0.00863)	(0.00397)
BM	0.0282***	-0.00308*
	(0.00413)	(0.00183)
CF	0.0136	0.900***
	(0.0128)	(0.00680)
CCE	0.0141	-0.114***
	(0.0125)	(0.00565)
BIG_4	0.00449	-0.00951***
	(0.00548)	(0.00199)
Constant	-0.0553**	-0.131***
	(0.0264)	(0.00938)
Year FE	YES	YES
Firm FE	YES	YES
Observations	21707	19766
R-square	0.031	0.792

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. CITY is instrument variable calculated as average biodiversity risk of other surrounding firms in the same three-digit zip code. The definition of other variables can be found in Appendix A*

4.3.4 Difference in difference

Table 14
Robustness test: difference in difference

VARIABLES	(1) ROA	(2) ROA
NEGD * TIME	-0.017**	-0.019**
	(0.008)	(0.008)
NEGD	-0.000	-0.000
	(0.006)	(0.007)
TIME	-0.015**	0.001
	(0.006)	(0.001)
SIZE	0.019***	0.020***
	(0.002)	(0.001)
LEV	-0.071***	-0.071***
	(0.006)	(0.006)
TAN	-0.032***	-0.037***
	(0.008)	(0.008)
BM	-0.028***	-0.028***
	(0.002)	(0.002)
CF	0.657***	0.652***
	(0.017)	(0.017)
CCE	-0.044***	-0.050***
	(0.008)	(0.008)
BIG_4	-0.005	-0.005
	(0.004)	(0.004)
Constant	-0.344***	-0.359***
	(0.035)	(0.028)
Observations	24,753	24,753
R-squared	0.516	0.506
Year FE	YES	NO
Firm FE	YES	YES

,and***indicate statistical significance at the 10%, 5% and 1% level, respectively. NGED is 1 if firms' biodiversity negative score larger than 0, and otherwise it is 0. TIME is a dummy variable equals to 1 if an observation is from period after 2012, and 0 the otherwise. The definition of other variables can be found in Appendix A*

In 2012, the Biodiversity Finance Initiative (BIOFIN) was launched by United Nations Development Programme. This global partnership promotes integration of biodiversity and ecosystem services with development policy, planning and budgeting, assessing financing needs for biodiversity management and conservation, enabling funding sources to meet financing needs. This initiative greatly raises the awareness on the nexus between biodiversity and finance, provoking the thinking and discussion on the role business should play to prevent biodiversity loss. As a result, we select 2012 as the intervention year. $NEGD_{\square}$ is a dummy variable that equals 1 if firm's biodiversity negative score is larger than 0 and 0 otherwise. $TIME_{\square}$ is a dummy variable that equals to 1 if an observation is from period after 2012, and 0 otherwise. As shown in Table 14, the interaction term is significant at 5% level, it indicates the robustness of our analysis.

5. Conclusions

With growing attention paid to biodiversity loss and the consequential risks on enterprises, it is in need to explore not only biodiversity risk in general but also the components of it. This research goes beyond the general relationship between biodiversity risk and financial performance, examining how does physical risk and transition risk impact on financial performance respectively by utilizing firm level biodiversity risk data following the methodology of Giglio et al. (2023), dependency and pressure rating from ENCORE, and firm level financial data from LESG Workspace. The dataset covers US listed companies from the year 2000 to 2023.

The results are as follows: (1) There is negative relationship between biodiversity risk and firms' financial performance, this negative relationship strengthened for firms with high pressure rating, this supports the hypothesis that biodiversity transition risk is negative related with financial performance; (2) The mechanism analysis shows that firms with high pressure rating are more likely to disclose biodiversity impact reduction policy and have higher production costs in the presence of biodiversity risk. This result support the hypothesis that biodiversity transition risk impacts on financial performance through

stakeholder engagement and production costs;(3) Overall, no significant evidence shows that firms with high dependency rating performs worse than those without. Further dissecting ecosystem services dependency into three main groups, it finds companies with high regulating and maintenance ecosystem services rating performs worse in the presence of biodiversity risk. The interpretation for this result is that physical risk takes a long period to materialize, and this process is usually gradual and invisible.

Additionally, we conducted several robustness tests for the baseline analysis which include propensity score matching, entropy balancing, replacement of outcome and treatment variables, instrument variable test and difference in difference test, the baseline results still hold and support the robustness of our analysis.

The implications of this research are multifold: First, it suggests that investors should take into account of companies' biodiversity risk profile, especially considering more risk premium for companies that are more susceptible to biodiversity transition risk by screening companies that put much pressure on biodiversity. At the same time, long term investors should not overlook the gradual materialization of physical risk shock to the business as the evidence from our analysis show that physical risk impact has not yet been reflected in firm's financial performance. Second, for regulators, they should continue to put pressure on the companies that impose high pressure on biodiversity conservation. At the same time, there are needs for regulators to come up with a framework to inform business about the biodiversity physical risk and take related unrealized costs into accounting procedure; Third, the companies should be transparent about its biodiversity risk exposure and adopt active biodiversity management approach to mitigate negative biodiversity risk impact on the profitability of the business.

Appendix A. Variable definitions

Variable	Definitions
BRE	10K biodiversity count score, assign 1 when a company's 10-K filing includes at least two sentences related to biodiversity, and 0 otherwise
BRE_N	10K biodiversity negative score, number of negative biodiversity sentence – number of positive biodiversity sentence; assign 0 to neutral or not mention
BRE_R	10K biodiversity regulation score, assign 1 when there are at least two biodiversity related sentences, and at least one biodiversity regulation related sentence, 0 otherwise
HP	Dummy variable that equals 1 if firms have High or Very High ENCORE pressure rating and 0 otherwise
HD	Dummy variable that equals 1 if firms have High or Very High ENCORE dependency rating and 0 otherwise
ROA	Net income divided by total assets
ROE	Net income divided by total equity of common shares
BM	Book-to-market ratio
CF	Operating cash flow scaled by total assets
CCE	Cash and cash equivalents scaled by total assets
SIZE	Natural logarithm of firm total assets
LEV	Liabilities divided by total assets
TAN	Tangibility, fixed assets over total assets
RG	Revenue growth, percentage of year over year change for revenue
BIG_4	Dummy variable equals to one if auditor of the firm is a big for auditor, zero otherwise
IRP	Dummy variable equals to 1 if firm has biodiversity impact reduction policy, zero otherwise
COGS	Cost of goods sold scaled by score
HPROV	Dummy variable that equals 1 if firms have High or Very High ENCORE provisioning services dependency rating and 0 otherwise
HREG	Dummy variable that equals 1 if firms have High or Very High ENCORE regulating and maintenance services dependency rating and 0 otherwise

HCUL	Dummy variable that equals 1 if firms have High or Very High ENCORE cultural services dependency rating and 0 otherwise
CITY	Variable calculated as average biodiversity risk of other surrounding firms in the same three-digit zip code.
NGED	Dummy variable equals to 1 if firm's biodiversity negative score is larger than 0 and 0 if the otherwise
TIME	Dummy variable equals to 1if observations are from the period after 2012, and 0 the otherwise

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