Biodiversity Risk *

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Abstract

We explore the effects of physical and regulatory risks related to biodiversity loss on economic activity and asset values. We first develop a news-based measure of aggregate biodiversity risk and analyze how it varies over time. We also construct and publicly release several firm-level measures of exposure to biodiversity risk, based on textual analyses of firms' 10-K statements, the holdings of biodiversity-related funds, and a large survey of finance professionals, regulators, and academics. Exposures to biodiversity risk vary substantially across industries in a way that is economically sensible and distinct from exposures to climate risk. We find evidence that biodiversity risks already affect equity prices: returns of portfolios that are sorted on our measures of biodiversity risk exposure covary positively with innovations in aggregate biodiversity risk. However, our survey indicates that market participants do not perceive the current pricing of biodiversity risks in equity markets to be adequate. We also construct several measures of biodiversity risk exposure across U.S. counties, but find little evidence that those exposures are priced in municipal bond markets.

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Over the past decade, investors, researchers, and policymakers have increasingly focused on managing the complex relationships between the modern economy and the health of our planet. For example, a series of international treaties have codified commitments to reduce carbon emissions in an effort to slow global warming, and there have been numerous efforts from the business and financial communities to address the various risks from climate change. On the academic side, the field of climate finance has rapidly developed into an active area of research (see Giglio et al., 2021b; Stroebel and Wurgler, 2021; Hong et al., 2020, for recent reviews). Yet, climate change is only one important dimension of the interaction between economic activity and the health of our planet. In this paper, we study a different and equally important dimension: the economic risks associated with *biodiversity loss.*

Throughout history, humans have relied on biodiversity—defined here as the sum total of genes, species, and ecosystems—to survive and thrive, and estimates of the annual economic value provided by biodiversity-related services are in the tens of trillions of dollars (Costanza et al., 1997). For example, diverse ecosystems are key to the production of food and nature-based materials such as timber (Duarte et al., 2009; Liang et al., 2016; Paul et al., 2020; Porto et al., 2020; Steffan-Dewenter et al., 2007); many medicines, including antibiotics and cancer drugs, are derived from natural compounds found in plants, animals, and microorganisms; and biodiverse ecosystems reduce the likelihood of disease outbreaks and improve resilience to climate change (Isbell et al., 2015; Keesing and Ostfeld, 2021). Given this multifaceted reliance of society on biodiversity, its degradation can have large social and economic effects, and the recent losses of ecosystem services have been estimated to cause damages of \$4trn to \$20trn per year (Kapnick, 2022). In addition to these physical risks from biodiversity loss, transition risks from regulatory and other responses to biodiversity loss—such as those resulting from policy committments made at the recent COP15 conference in Montreal—can also have substantial effects on economic activity and asset values.

A key reason why biodiversity risk has been largely neglected by researchers in economics and finance is its complexity and the associated difficulty of measuring and quantifying its various elements. In this paper, we propose a systematic way to measure aggregate biodiversity risk so that it can be studied quantitatively with the analytical tools of finance. We also develop and publicly release several measures of the exposures of firms, industries, and locations to biodiversity risks. Our exposure measures generally line up with investors' views about biodiversity risks as elicited through surveys and as reflected in asset prices. Our analysis identifies biodiversity risk as an important new dimension of risk that is distinct from climate risk, and we conclude that academic research should increasingly focus on the role that financial markets can play in managing biodiversity-related economic risks.

To motivate our analysis, we conduct a broad survey of the perceptions of biodiversity risks among finance academics, professionals, public sector regulators, and policy economists from around the world. We received a total of 668 survey responses. The survey shows broad and substantial concerns about the economic effects from biodiversity loss over relatively near-term horizons. Around 70% of respondents perceive physical and transition biodiversity risks to have at least moderate financial materiality for firms in the United States, with private sector respondents reporting the highest perceived financial materiality of these risks.

We next move to quantify the aggregate amount of biodiversity risk over time. A key issue with measuring risks such as those related to biodiversity loss is that they often unfold slowly over long horizons, making it hard to quantify risk and risk exposures using standard statistical tools. To overcome these challenges, we follow the approach developed in Engle et al. (2020) and build a biodiversity risk index using *news* about such risks extracted from newspaper coverage of topics associated with biodiversity loss. This high-frequency measure allows us to quantify the immediate impacts of changes in expectations about damages and regulations related to biodiversity loss, even if they might only materialize in the future.

Specifically, we construct a biodiversity news index by analyzing articles in the New York Times (NYT). To identify articles related to biodiversity loss, we develop a dictionary containing a list of relevant terms such as "ecosystem" and "deforestation." This dictionary is used to identify articles in the NYT that cover biodiversity risks. We classify the sentiment of these articles using the Bidirectional Encoder Representations from Transformers, or BERT, a standard model from the natural language processing literature. BERT assigns each sentence a positive, negative, or neutral sentiment score, and this information is aggregated to compute a daily "NYT-Biodiversity News Index". We also analyze data on Google search activity for terms like "biodiversity loss" and "species loss" to construct a second index that tracks public attention to biodiversity risks, and aggregate the results into a monthly "Google-Biodiversity Attention Index". We validate both indices, which are substantially correlated, by showing that they spike in times with important events regarding biodiversity risk (e.g., during ecosystem disasters or international summits to limit biodiversity loss).

Next, we study the cross-sectional variation in biodiversity risk exposures. Different sectors of the economy vary in their dependence on natural capital, and therefore their exposures to physical biodiversity risk. Similarly, the activities of sectors with larger effects on the environment will be more affected by regulatory interventions to reduce biodiversity loss. However, the absence of standardized disclosure frameworks for physical and transition biodiversity risks makes quantifying these exposures hard. We thus propose and compare several new ways to measure firms' biodiversity exposures, using three different data sources: firms' 10-K statements; the opinions elicited in our survey of financial professionals, academics, and regulators; and the portfolio holdings of funds focused on biodiversity. We release our measures of biodiversity risk exposures at `www.biodiversityrisk.org`.

Our first set of measures of biodiversity risk exposures, available at the firm level, is based on textual analysis of firms' 10-K statements to identify discussions of biodiversity-related risks. The second measure is created at the industry level from our survey of academics and professionals. The survey asked respondents to select the industries most negatively affected by biodiversity loss, distinguishing explicitly between both physical and transition risks. Our third measure of biodiversity risk exposures is based on the holdings of four biodiversity-related funds. It is calculated by comparing the weight of an industry in the market portfolio to its weight in the biodiversity funds' portfolios, based on the assumption that industries that are underweighted relative to the market are negatively exposed to biodiversity risks. All three measures are substantially correlated in the cross-section: industries ranked high on biodiversity risk exposure on one measure generally also rank high on the other measures.

The sectors with the highest average biodiversity risk exposures include energy, utilities, and real estate, while firms in the semiconductor, software, and communication services sectors have minimal exposure to biodiversity risks.

To better understand the economic mechanisms driving our estimated risk exposures, we study the 10-K statements of firms in industries that are differentially exposed to biodiversity risks. Both physical and transition risks are frequently mentioned. For example, we find that firms in the energy sector are exposed to biodiversity transition risks because of their exploration, drilling, and refining activities, which can affect the ecosystem and are potentially a target for future regulations. Similarly, utility firms, including those producing solar and wind energies, face regulations on species and habitat protection that can limit their operations, and the real estate industry faces restrictions on developments in areas with high biodiversity. Firms also report facing a variety of physical biodiversity risks. For example, firms in the pharmaceutical sector report relying on biodiversity for drug discovery.

We then use our measures of news about aggregate biodiversity risk as well as our firm- and industry-level risk exposures to explore the extent to which biodiversity risks are currently incorporated into equity prices. To do so, we form equity portfolios of industries sorted by their biodiversity risk exposures. The portfolios hold long positions in industries with low biodiversity risk exposures and short positions in industries with high biodiversity risk exposures. If biodiversity risk is priced, the return of these biodiversity-risk-sorted portfolios should covary with the aggregate biodiversity news index, effectively behaving like a hedging portfolio for biodiversity risk. We find that the correlations between the returns of our biodiversity hedging portfolios and the biodiversity risk index are positive, with magnitudes as large as 0.2. These correlations are comparable to those obtained by climate hedging portfolios when evaluated against aggregate climate news, and, more generally, to the hedging performance of portfolios built to hedge other macro risks such as consumption or GDP.

To investigate whether our measures of biodiversity risk exposure are simply recasting information from other firm characteristics, we compare the hedge performance of our biodiversity risk measures with that of hedge portfolios constructed using other firm characteristics—specifically, the 207 characteristics in the "factor zoo" of Chen and Zimmermann (2022)—and find that our measures of biodiversity exposure perform significantly better than the vast majority of this universe of characteristics in hedging aggregate biodiversity risk (given the large number of factors and the well-known multiple hypothesis problem, one would expect some to work well as a hedge just by chance). Overall, the evidence suggests that biodiversity risk has been at least partly priced in the cross-section of equities over the last decade.

We also measure the exposure of U.S. counties to various biodiversity risks, using information on both the ecology and the economy of the counties. In terms of ecology, protected areas are concentrated mainly in Western United States, while endangered species are more prevalent in coastal regions. On the other hand, industries with large exposures to biodiversity risks are disproportionately located in the central United States. We assess whether the returns of portfolios of municipal bonds, sorted by the various biodiversity risk exposures of their issuers' locations, covary with aggregate biodiversity risk. We find no such evidence, though the illiquid nature of municipal bonds complicates an interpretation of these results as definitive evidence against the pricing of biodiversity risk in municipal bond markets.

We conclude by reviewing evidence from our survey on market participants' perceptions of whether biodiversity risks are adequately priced in financial markets. About half of the respondents believe that these risks are not sufficiently priced across stock, commodity, sovereign debt, and real estate markets, while 14%-19% of respondents believe that they are correctly priced. Only a handful of respondents believe that biodiversity risks are overpriced in these asset markets (while about 35% of respondents had no opinion).

Throughout the paper, we explore the relationship between biodiversity risks and climate risks. The two risks are conceptually distinct, as biodiversity risk focuses on the threats to the variety of life on Earth and its consequences, while climate risk relates to the potential negative consequences of a change in the climate system. Despite this conceptual distinction, the two risks are interconnected in that climate change can exacerbate biodiversity loss, and biodiversity loss can drive climate change, for example through the destruction of carbon sinks. Given the recent academic and policy interest in climate change and its economic implications, it is important to distinguish the two types of risk not only qualitatively, but also quantitatively. We do so in several ways. First, we show that the aggregate biodiversity news index behaves differently from analogously constructed climate news indices; second, we document that climate risk exposures and biodiversity risk exposures are only weakly related in the cross-section of industries; and finally, we show that portfolios built for hedging climate risk do not perform well at hedging biodiversity risk, and vice versa.

Our work contributes to a quickly growing literature that explores the interaction between financial markets, asset prices, and the health of our planet. Much recent research has studied the physical and transition risks relating to climate change (e.g., Alekseev et al., 2022; Engle et al., 2020; Giglio et al., 2023; Pástor et al., 2021; Bolton et al., 2020; Grippa et al., 2019; Bolton and Kacperczyk, 2022; Pástor et al., 2021, 2022; Choi et al., 2020; Giglio et al., 2021b; Bernstein et al., 2019; Baldauf et al., 2020; de Boyrie and Pavlova, 2020; van Benthem et al., 2022; Acharya et al., 2023). Giglio et al. (2021b), Stroebel and Wurgler (2021), and Hong et al. (2020) provide recent reviews of this literature. Much less work has been done to understand the effect of biodiversity risks on asset values and economic activity. For example, our paper is the first, to our knowledge, to provide quantitative measures of aggregate biodiversity risk and to study how it is priced in the cross-section of equity markets. By addressing this research gap, we respond to the call for more research in Karolyi and Tobin-de la Puente (2022) and provide publicly available data sources to spur follow-up work on biodiversity risks at `www.biodiversityrisk.org`. Among the most related papers studying financial or economic aspects of biodiversity loss, we note that Dasgupta (2021) presents an overview of the current state of global biodiversity and the economic factors that contribute to its decline, and Flammer et al. (2023) focuses on the financing of biodiversity conservation projects.

1 Biodiversity Risks: Perception and Measurement

The economic and financial risks relating to biodiversity can be broadly divided into physical risks from the actual loss of biodiversity and transition risks from responses by regulators and consumers to reduce biodiversity loss (see OECD, 2019; IFC, 2019; BCG, 2021).

Physical risks encompass the financial and economic effects from the loss of biodiversity and ecosystem services. These services include the supply of raw materials like food, fiber, and fuel; the regulation of climate, water, soil, and air quality; and the support of pollination, nutrient cycling, and soil formation. For example, firms relying on specific natural resources, such as the timber, may face scarcity or quality issues due to deforestation or habitat loss. This can lead to increased raw material costs and deteriorating supply chains. Similarly, biodiversity loss can negatively affect the R&D process in the pharma and biotech sectors. In addition to such direct effects, biodiversity loss can raise the likelihood of the emergence of various diseases, by disrupting the balance of the ecosystem, and increase vulnerability to damages from climate change, for instance by reducing carbon sequestration capacity.

Besides the physical risks associated with biodiversity loss, firms may also be affected by risks from an increased focus of regulators and consumers on the protection of biodiversity. For example, policies aimed at protecting biodiversity, such as land-use regulations and sustainable forestry requirements, may result in changes to asset values across a range of industries. Biodiversity transition risks also come from changing consumer preferences, such as shifts away from palm oil by consumers concerned about its effect on deforestation. In addition, legal and reputational biodiversity risks affect firms by increasing the cost from causing ecological disasters such as oil spills.

In this section, we aim to better understand the importance and evolution of these biodiversity risks from an aggregate perspective. We first discuss findings from a survey of academics, financial professionals, and regulators about the relative importance of various biodiversity risks over different time horizons. We then describe several new measures of aggregate biodiversity risks over time, and highlight that the time-series movements of biodiversity risk are distinct from those of climate risk, which have been studied extensively in the academic literature.

1.1 Perceptions of the Importance of Biodiversity Risks

To measure perceptions about the importance of biodiversity risks, we surveyed finance researchers, professionals, and public sector employees in Q1 2023. To reach academics, we collected email addresses of about 4,500 faculty at top-100 finance departments.[1] To reach practitioners, we contacted about 7,000 NYU Stern and Yale SOM graduates working in finance. To reach those involved in policy, we invited about 3,000 researchers or policymakers working in the finance-related groups of about 35 relevant public sector institutions to participate in our survey (see Appendix A.4 for the full list of these institutions).

[1] We used the ranking maintained at ASU based on the total number of articles published in the Journal of Finance, Journal of Financial Economics, and Review of Financial Studies from 2010 through 2023.

In total, we received 668 complete responses for an overall response rate of about 4.5%.[2] 48% of responses were from academic researchers, 34% from financial professionals, and 18% from financial regulators or public-sector researchers. Our respondents' locations tilt toward North America (62%) and Europe (23%), with respondents from Asia and the Rest of the World making up 9% and 5% respectively. Appendix Table A.7 contains summary statistics and cross-tabulations of the demographic information reported by respondents.

Appendix A.3 shows the flow of the survey. The first question asked respondents about how worried they were about both ecosystem diversity loss and species diversity loss. The level of concern about both types of biodiversity loss is high, with about 70% expressing substantial personal concerns. To investigate perceptions of the financial and economic implications of biodiversity risks, we ask survey participants to rate the financial materiality of physical risk and transition biodiversity risk for U.S. firms. We also ask respondents over what time horizon they expected these risks to materialize. Table 1 presents the responses for different groups of respondents. Both physical risk and transition risk are generally perceived to be material, in particular by respondents in the private sector as well as by respondents located in Africa, South America, and Australia. While about 20% of respondents believe that physical and transition biodiversity risks are already materializing today, transition risks are generally believed to be somewhat more likely to matter over the coming five years.

Appendix Table A.2 shows several responses to an open question asking if there are any particular ways in which biodiversity risks are important in participants' professional life. Respondents mentioned both physical risks ("I co-run an investment fund in farmland and timberland, which are directly affected by these risks") and transition risks ("Regulatory risk related to biodiversity are a chief driver of long-term uncertainty in the energy markets in which I work"). Many survey participants discussed mechanisms through which biodiversity loss affects the economy, for example through the exposures of specific industries (as in the examples above), or at the aggregate level (as in the following responses: "Biodiversity risks are a serious threat to financial stability and the resilience of financial companies"; "Loss of biodiversity and area for animals to move closer to cities, causing a great chance for diseases to spread to humans, which may cause another pandemic"). Overall, the survey shows that biodiversity is a growing concern among ESG analysts, fund managers, VCs, and management consultants, especially those working with the energy, materials, and construction sectors, as well as among academics and public sector employees.

1.2 Measuring Aggregate Biodiversity Risk

Table 1 suggests a substantial degree of concern about biodiversity risks. In this section, we construct several indices that allow us to measure attention and concern related to biodiversity risks over time. While biodiversity loss can have substantial economic costs, it is relatively slow-moving, with many of the worst possible outcomes materializing over a period of decades (see Magurran, 2021). This complicates the quantification of the risk and

[2]This response rate is comparable to that in other surveys used by finance researchers, such as 7.5% in Stroebel and Wurgler (2021) and 2.5-4% in Giglio et al. (2021a)

Table 1: Biodiversity Risk Perceptions

		Role			Location				Biodiversity Concern			
	Pooled	Academic Institution	Private Sector	Public Sector	North America	Europe	Asia	ROW	Very High	High	Low	No Concern
Physical Risk Importance (%)												
Not at all important	8	9	9	5	9	6	9	6	1	3	9	100
Slightly important	24	26	23	20	26	20	26	14	6	27	91	0
Moderately important	35	37	28	40	34	36	38	26	19	69	0	0
Very important	34	28	40	35	31	38	28	54	73	0	0	0
Transition Risk Importance (%)												
Not at all important	7	7	6	11	8	6	7	9	1	1	9	100
Slightly important	20	22	19	18	22	19	19	11	8	17	91	0
Moderately important	42	46	34	46	40	50	36	40	26	82	0	0
Very important	30	25	41	25	30	25	38	40	66	0	0	0
Physical Risk Materialization (%)												
Already today	23	18	29	24	24	18	19	29	32	15	12	13
1 to 5 years	10	8	10	14	9	9	5	23	11	9	8	7
5 to 30 years	46	51	43	41	45	52	43	43	45	57	36	7
More than 30 years	17	18	14	19	17	17	22	3	10	17	35	30
Never	5	6	4	1	4	4	10	3	1	2	9	43
Transition Risk Materialization (%)												
Already today	20	16	27	17	23	14	16	23	27	14	15	10
1 to 5 years	26	28	25	24	25	29	22	34	33	23	15	7
5 to 30 years	41	44	34	47	40	44	43	34	33	54	41	13
More than 30 years	8	7	10	7	9	7	9	3	4	7	20	27
Never	5	5	4	6	3	7	10	6	2	2	9	43

Note: For the first two blocks, participants were asked: "Biodiversity risks for investors and firms are often divided into (i) physical risks coming from actual changes in biodiversity (e.g., reduced pollinators, freshwater scarcity) and (ii) transition risks coming from changes in the regulatory environment to combat biodiversity loss (e.g., the Clean Water Act). Please rate the financial materiality of these risks for corporations in the United States. 1- Physical Risk; 2- Transition Risk". For the last two blocks, participants were are: "Over what time horizon, if any, do you expect these biodiversity risks to materialize?", where biodiversity risk is either the physical risk or transition risk.

of different assets' exposure to that risk. To explore the evolution of biodiversity risk over time, we build on insights of Engle et al. (2020), who suggest that in the presence of a slow-moving long-term risk such as climate change or biodiversity loss, risk exposures can be explored by obtaining higher-frequency measures of *news* about future damages arising from the risk (see Ardia et al., 2020; Stecula and Merkley, 2019, for further examples of news-based measures of climate risk built on this insight). Based on this idea, we construct an index of biodiversity *news* as reported in the New York Times (NYT). We also construct a related measure capturing public *attention* to biodiversity risks using Google searches.

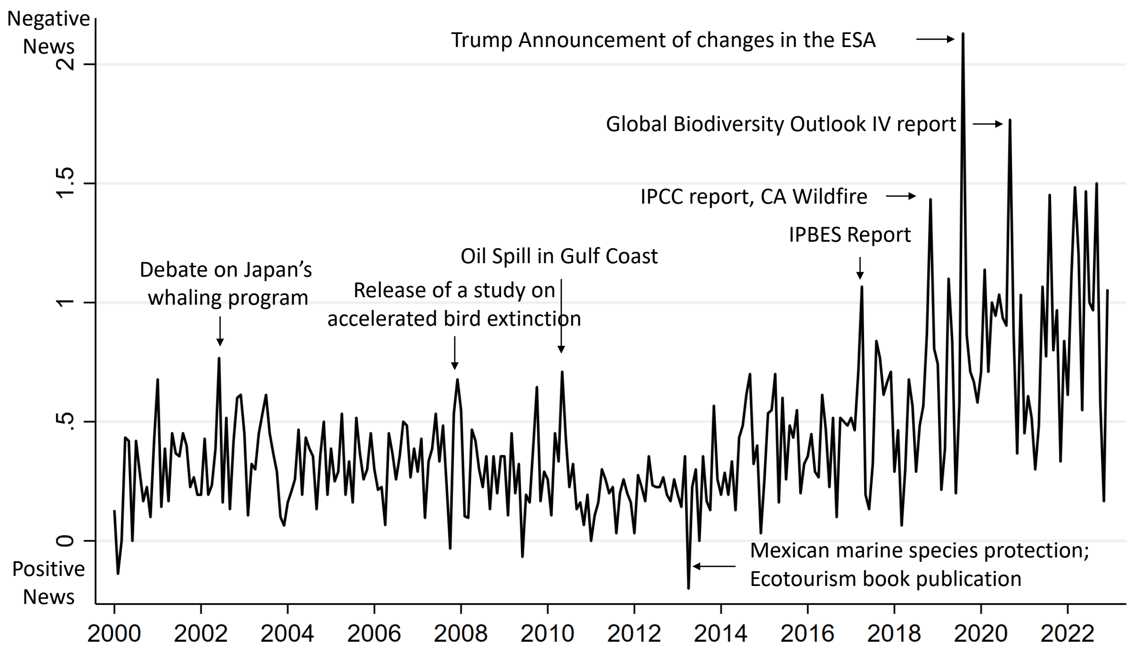
The NYT Biodiversity News Index. The first step to building our measure of biodiversity news is to identify news articles that cover biodiversity. To do so, we build a Biodiversity Dictionary that contains the following biodiversity-related terms: biodiversity, ecosystem(s), ecology (ecological), habitat(s), species, (rain)forest(s), deforestation, fauna, flora, marine, tropical, freshwater, wetland, wildlife, coral, aquatic, desertification, carbon sink(s), ecosphere, and biosphere. These words were selected based on their cosine similarity to "biodiversity" in Google's *word2vec*[3] implementation. Using this dictionary, we identify a sentence as biodiversity related if it contains at least one of these terms, excluding instances of unrelated combinations such as "software ecosystem" (see Appendix A.4 for details). We identify articles containing at least two biodiversity sentences as covering biodiversity.

News about biodiversity loss can either be positive or negative; for example, an article can report that biodiversity loss is progressing faster or slower than previously anticipated. To separately identify such news stories, we adopt the Bidirectional Encoder Representations from Transformers (BERT) model to classify each of the selected biodiversity sentences to determine whether it expresses a positive or negative sentiment (Devlin et al., 2018). Sentences with positive sentiment get assigned a score of "+1", negative sentences get assigned a score of "-1", and neutral sentences get assigned a score of "0". For example, the following sentence gets classified as having a positive sentiment: *"In the mid-2000s, African leaders envisioned creating a huge swath of green that could help combat desertification and land degradation."* In contrast, a negative sentiment is assigned to *"Environmental problems remain, including overfishing and the erosion and deforestation left from earlier eras."* Appendix Table A.3 presents further examples of biodiversity related sentences alongside their BERT sentiment classifications. We assign an article to have positive (negative) sentiment if the average sentence sentiment scores for all biodiversity sentences in the article is positive (negative). About 6.6% of articles get classified as positive, 77.9% as neutral, and 15.7% as negative.

To measure the overall sentiment of biodiversity news on a given day, we construct the NYT-Biodiversity News Index as the number of negative biodiversity articles minus the number of positive biodiversity articles on that day. Therefore, higher values of the NYT-Biodiversity News Index correspond to more negative news about biodiversity risks. This daily measure of biodiversity news can be easily aggregated to the weekly or monthly level. Figure 1 plots the monthly NYT-Biodiversity News Index and adds labels to events relevant

[3]We use the pre-trained vectors trained on part of Google News dataset (about 100 billion words). The model contains 300-dimensional vectors for 3 million words and phrases.

Figure 1: NYT-Biodiversity News Index



Note: Monthly NYT-Biodiversity News Index from 2000 to 2022, annotated with biodiversity-relevant news announcements. ESA: Endangered Species Act; IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services; IPCC: Intergovernmental Panel on Climate Change.

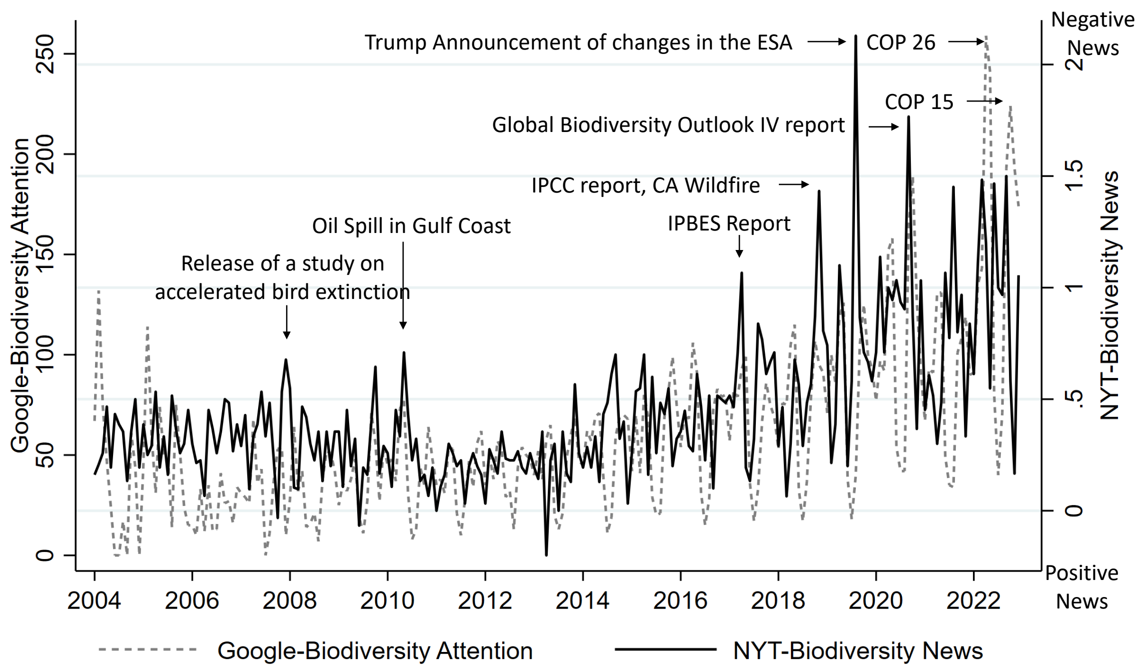
to biodiversity. The intensity of negative biodiversity news coverage has steadily increased since about 2015. The index spikes around salient biodiversity-related events, such as changes to Endangered Species Act (ESA) in 2019 and the release of biodiversity-related reports. We have explored other ways of constructing our biodiversity news index, for example by measuring an article's sentiment as the average sentiment of all biodiversity related sentences in that article, and by measuring the the per-period overall biodiversity sentiment as the average sentiment of all biodiversity related articles. The patterns described in this paper are robust to such variations in the construction of our biodiversity risk news series.

Google Biodiversity Attention Index. We also measure U.S. public attention to biodiversity risks by analyzing Google searches for the terms "biodiversity loss", "ecosystem services", and "species loss."[4] Since Google Trends data are not available at the daily level, we construct a monthly measure. For each of the three terms, the Google search series represents search interest relative to the highest point for the U.S. over the full time sample (from 2004 to 2023). Our Google-Biodiversity Attention Index is created as the sum of the search index series for each of the terms. Figure 2 plots this series alongside the NYT-Biodiversity News Index. Public attention to biodiversity loss has been gradually increasing over time,

[4] We did not use the full Biodiversity Vocabulary as in our analysis of NYT coverage of biodiversity loss, since we cannot filter out unrelated terms such as "software ecosystem." Therefore, we selected several composite terms that we believe allow us to explore people's attention to biodiversity risks.

with marked spikes during climate- and biodiversity-related conferences such as COP 15. The amount of negative biodiversity-related news and public attention to biodiversity loss often coincide, and the two series have a correlation of about 0.47 (see Table 2).

Figure 2: NYT-Biodiversity News Index vs. Google-Biodiversity Attention Index



Note: Monthly Google-Biodiversity Attention Index from 2004 to 2022, overlaid against the NYT-Biodiversity News Index and annotated with relevant events. COP 26: 2021 United Nations Climate Change Conference of the Parties; COP 15: 2022 United Nations Biodiversity Conference.

1.3 Biodiversity Risk vs. Climate Risk

As discussed above, climate and biodiversity risk are related but distinct concepts. In this section, we explore the relationship between the two risks quantitatively, by comparing our biodiversity risk series with corresponding climate risk series.

To do this, we first build a new climate news series, the NYT-Climate News Index, by applying the methodology described in Section 1.2, identifying climate-related sentences with the terms "climate change" and "global warming." As alternatives to our own climate news series, we also consider four of Faccini et al. (2021)'s climate news indices: international climate summits, global warming, natural disasters, and the narrative index.[5] These measures, which cover news about both physical and transition climate risks, are available at a daily frequency between January 2000 and November 2019. We aggregate them to the monthly frequency by taking the average of the daily series.

[5]The international climate summits, global warming, and natural disasters indices measure news coverage of the respective topics; the narrative index is constructed by manually reading and classifying 3,500 articles. The international climate summits and narrative indices capture news about climate transition risk, while the global warming and natural disasters indices are more likely to capture news about physical climate risk.

Table A.8 shows the pairwise correlation across these various news indices using monthly data from 2004 to 2022. The first two columns are the NYT-Biodiversity News Index and the Google Biodiversity Attention Index. The next column is the NYT-Climate News Index and the last four columns are the Faccini et al. (2021) indices. Since the measures of Faccini et al. (2021) end in 2020, we only use data up to then for correlations with these measures.

Table 2: Correlation Across Measures of Aggregate Risk

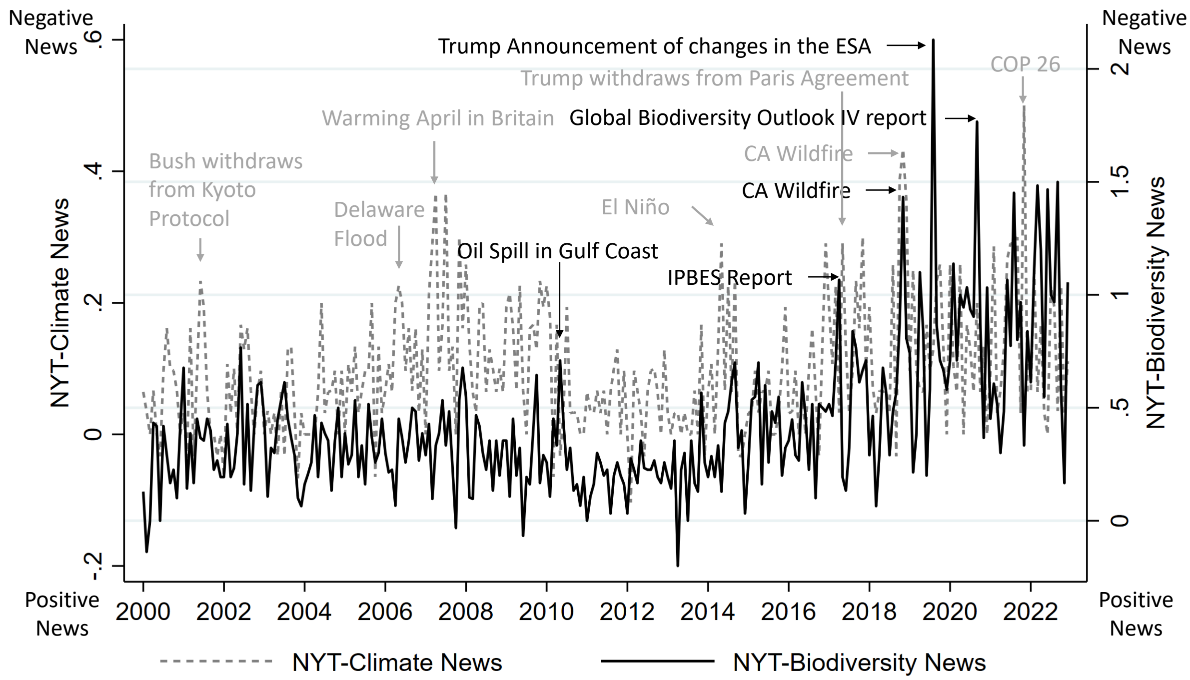
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Biodiversity Risk Measures							
(1) NYT-Biodiversity News	1.00						
(2) Google-Biodiversity Attention	0.47	1.00					
Climate Risk Measures							
(3) NYT-Climate News	0.22	0.08	1.00				
(4) Faccini et al (2021): Internat. Summit	−0.20	−0.26	0.20	1.00			
(5) Faccini et al (2021): Global Warming	−0.09	−0.03	0.29	0.66	1.00		
(6) Faccini et al (2021): Natural Disaster	0.14	−0.10	0.31	0.52	0.64	1.00	
(7) Faccini et al (2021): Narrative	−0.18	−0.29	0.02	0.56	0.40	0.35	1.00

Note: Pairwise monthly correlation across biodiversity and climate risk measures. NYT-based and Google-based measures are based on data from 2004-2022, while Faccini et al (2021) indices use data from 2004-2020. The corresponding table using data from 2010-2022 is presented in Appendix Table A.1.

As mentioned above, the correlation between the biodiversity news and biodiversity attention indices is about 0.47: on average, attention to biodiversity risk increases in months with negative biodiversity news. In contrast, the correlation between the biodiversity news index and the five climate news indices ranges between -0.20 and 0.22. These results suggest that while climate risk and biodiversity news are related to some extent, they are not the same.

Figure 3 illustrates the differences between the biodiversity and climate news series. The solid black line and black annotations correspond to the NYT-Biodiversity News Index and related biodiversity risk events, while the dotted grey line and grey annotations correspond to the NYT-Climate News Index. Note that both series are generated with the same method and based on the same data, and differ only in the keywords used to select articles. Months with negative biodiversity-related news do not necessarily correspond to months with negative climate news. For example, in August 2019, the Trump administration announced that it would change the way the Endangered Species Act was applied, making it easier to remove a species from the endangered list and weakening protections for threatened species. This led to substantial negative newspaper coverage of biodiversity-related topics, and thus a sharp increase in the NYT-Biodiversity News Index, while the NYT-Climate News Index stayed relatively stable. Similar events include the release of the IPBES Report in 2014 and the 2010 Oil Spill in the Gulf Coast. Conversely, climate-related events, such as Bush's withdrawal from the Kyoto Protocol, Trump's withdrawal from the Paris Agreement, and COP 26, as well as natural disasters such as the Delaware flood, did not result in spikes in the biodiversity news index. Finally, some natural disasters were followed by both negative climate and negative biodiversity news: for example, the 2018 California Wildfires were connected to climate change but also caused habitat and species loss.

Figure 3: NYT-Biodiversity News vs NYT-Climate News



Note: Monthly NYT-Climate News Index from 2000 to 2022, overlaid against the NYT-Biodiversity News Index, and annotated with relevant news announcements.

2 Firm-Level Measures of Biodiversity Risk Exposures

Beyond quantifying aggregate biodiversity risk, we are also interested in exploring how biodiversity risk exposures vary across different firms and industries. For instance, the World Economic Forum (2022) states that the three sectors most reliant on natural capital are construction, agriculture, and food and beverages. Based on this assessment, firms in those sectors would be most substantially exposed to physical biodiversity risks. Similarly, sectors with substantial land use, such as the energy sector, might be particularly impacted by biodiversity transition risks. To improve our understanding of the effects of biodiversity risk on the economy, we need a systematic way to quantify these cross-sectional risk exposures.

A number of data vendors provide measures of firms' physical and transition *climate* risk exposures, though there are substantial doubts about the quality of these measures (see, for example, Billio et al., 2021). Similar data for firms' biodiversity risk exposures are not broadly available,[6] and standardized disclosure frameworks for biodiversity risk are still under development (Taskforce on Nature-related Financial Disclosures, 2022). In this

[6]Some data providers have some information on firms' activities with respect to biodiversity protection. For example, Refinitiv provides a score that measures whether a "company reports on initiatives to protect, restore or reduce its impact on native ecosystems and species, biodiversity, protected and sensitive areas." However, such measures are, at best, a rather imperfect proxy for firms' biodiversity risk exposures.

section, we therefore propose and compare several new ways to measure firms' biodiversity risk exposures, using different data sources: (i) firms' 10-K statements, (ii) the opinions elicited in our survey of financial professionals, academics, and regulators, and (iii) the portfolio holdings of funds focused on biodiversity. The first measure is available at the firm level, the others only at the industry level. We publicly release our measures of biodiversity risk exposures at `www.biodiversityrisk.org`.

2.1 Measures of Biodiversity Risk Exposure

10K-Biodiversity-Count Score. Our first firm-level measure of biodiversity risk exposures is based on textual analysis of firms' 10-K statements.[7] We identify biodiversity-related sentences in 10-K statements using regular expression searches for the same biodiversity dictionary used to construct the NYT-Biodiversity News Index, again excluding sentences with unrelated terms. If a 10-K statement contains at least two sentences related to biodiversity, we assign a 10K-Biodiversity-Count Score of "1" to this company in that year; if there is no mention of biodiversity-related terms, we assign a score of "0". We find that about 3.8% of all 10-K statements mention biodiversity between 2015 to 2020. The following are two examples of biodiversity-related sentences from 10-K statements, the first referencing transition risk exposures, and the second referencing physical risk exposures.

> In addition, future regulation of, or litigation concerning, the use of timberlands, the protection of endangered species, the promotion of forest biodiversity, and the response to and prevention of wildfires, as well as litigation, campaigns, or other measures advanced by environmental activist groups, could also reduce the availability of the raw materials required for our operations. [Enviva Partners LP, 2017 10-K filing]

> If this infrastructure were to become damaged due to natural or other disasters such as the oil spill that resulted from the Deepwater Horizon incident in 2010, then it is possible that environmental damages to the area and ecosystem could result. If these environmental damages occurred, they could have a material adverse effect on the Company's business, results of operation, and financial condition. [Omega Protein, 2015 10-K filing]

10K-Biodiversity-Negative Score. The 10K-Biodiversity-Count Score combines mentions of biodiversity as both a risk and an opportunity for firms. To separate such mentions, we construct a second measure of biodiversity risk exposure, the 10K-Biodiversity-Negative Score, based on sentiment analysis of the 10-K sentences mentioning biodiversity-related

[7] A 10-K statement is a comprehensive report filed annually by publicly listed companies with the U.S. Securities and Exchange Commission (SEC). It provides a detailed overview of a company's performance, including both structured financial metrics and unstructured textual information, such as management's discussion and analysis, business overview, and risk factors. We collect firms' 10K statements from 2001 to 2020 through the SEC's EDGAR database.

terms. Specifically, we use the BERT model to classify each biodiversity related sentence into positive, neutral, and negative sentiments. The two previous 10-K excerpts are assessed to have a negative sentiment by BERT; the following are two examples of a biodiversity-related 10-K mention that received a positive sentiment classification from BERT (Appendix Table A.4 presents further examples).

> We believe that the growth of hemp could significantly reduce deforestation by providing the same products that trees are able to supply. [Celexus Inc, 2019 10-K filing]

> The Company follows Sustainable Forestry Initiative ('SFI') Standards that promote sustainable forest management in North America through the use of core principles, objectives, performance measures and indicators to protect water quality, biodiversity, wildlife habitat, species at risk, and forests which have exceptional conservation value. [DELTIC TIMBER CORP, 2017 10-K filing]

About 5.4% of biodiversity related sentences are classified as positive, 19.4% as negative, and the remaining as neutral. For each firm-year, we count the number of positive and negative sentences and compute the firm 10K-Biodiversity-Negative Score as the number of negative biodiversity sentences minus the number of positive sentences. Between 2015 and 2020, among 10-K statements mentioning biodiversity-related issues, 36.1% do so in a predominantly negative way and 5.6% in a predominantly positive way.[8]

10K-Biodiversity-Regulation Score. When firms mention biodiversity in their 10-K statements, some explicitly express their concerns about the biodiversity risks stemming from stricter regulations. To explicitly measure these regulation biodiversity risks faced by firms, we construct a third 10K-based measure that selects biodiversity risk sentences that also contain at least one of the following terms: law(s), regulation, Act, ESA, discharge, or restriction. Appendix Table A.4 shows several examples of such sentences. We assign a 10K-Biodiversity-Regulation Score of "1" if the 10-K statement of a company contains at least two biodiversity risk sentences and at least one of them is a biodiversity regulation risk sentence. Between 2015 and 2020, about 2.9% of all 10-K reports (and 74.9% of all 10-K reports discussing biodiversity) discuss biodiversity-related regulation risks.

Survey-Based Measures of Biodiversity Risk Exposures. We construct another measure of biodiversity risk exposures—this time at the industry level—based on responses received in our survey of finance academics, professionals, and regulators. The survey asked participants to select the industries that they believe to be most negatively affected by (i) physical risks arising from biodiversity loss, and (ii) biodiversity-related transition risks (see Appendix Figure A.3.4). We provided 15 possible industry options to choose from, created

[8] Firms that do not mention biodiversity-related topics in their 10-K statement and firms that only include neutral sentences are assigned a score of 0.

by combining several of the 24 4-digit GICS industries.[9] We quantify an industry's physical and transition biodiversity risk exposure as the share of survey respondents who select each industry as being particularly affected by the risk.

Holding-Based Measure of Biodiversity Risk Exposures. In response to growing concerns about the economic effects of biodiversity loss, some asset managers have begun to introduce investment vehicles designed to help investors mitigate biodiversity risks in their portfolios. Our last approach to measuring biodiversity risk exposures is built on information about the holdings of these biodiversity funds.

To construct the Holding-based Biodiversity score, we explore four biodiversity-related funds: HSBC World ESG Biodiversity Screened Equity ETF, AXA IM ACT Biodiversity Equity ETF, Ossiam Food for Biodiversity ETF, and Trillium ESG Global Equity Fund. The first three Biodiversity ETFs were designed to hold companies that are acting positively for biodiversity by reducing or limiting the negative impact of human activities on biodiversity, while Trillium is an actively managed fund *"designed to address the risks and opportunities created by the increasing constraints on natural capital."*

We obtain the portfolio holdings from the funds' websites and Refinitiv Workspace and focus on North American common stocks. We obtain prices from CRSP and GICS industry codes from Compustat by merging the stocks on their CUSIP identifiers. We define the holding-based biodiversity score of fund f for industry I as:

$$HoldingScore^{I}_{t,f} = w_{I,t,M} - w_{I,t,f} \tag{1}$$

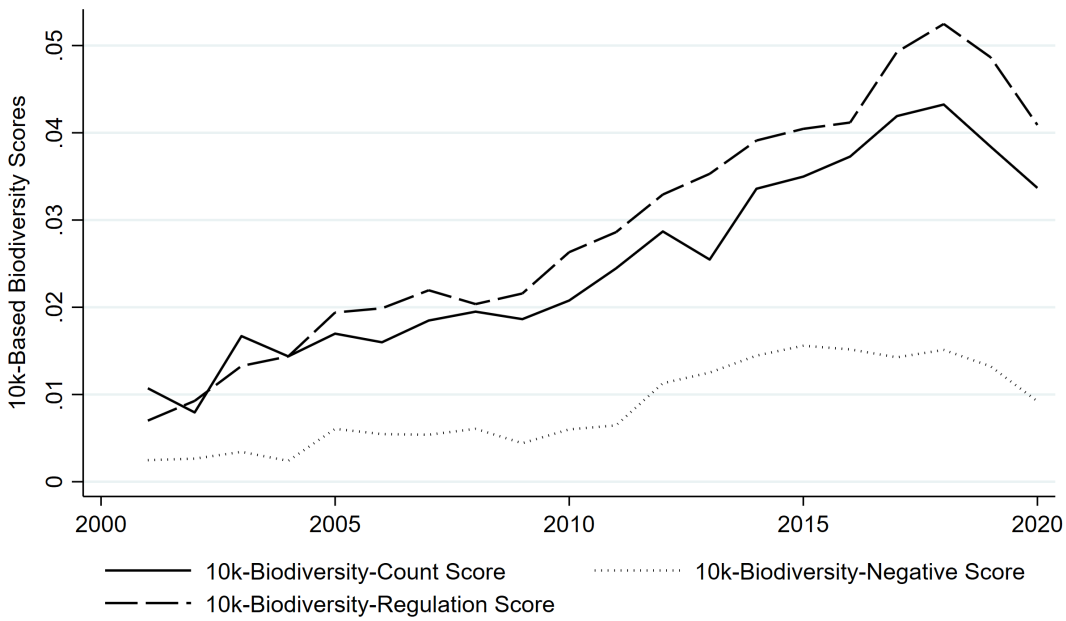
where $w_{I,t,M}$ is the weight of industry I in the market portfolio (i.e., based on the industry's market cap) at time t, and $w_{I,t,f}$ is the weight of industry I in the fund's portfolio. When a fund underweights an industry relative to the market, the score will be positive: we interpret this as the industry being negatively exposed to biodiversity risk. We compute this score for each fund and then average across funds to get the industry-level holding-based score (the average pairwise correlation of $HoldingScore^{I}_{t,f}$ across different funds is 0.24). Since the ETFs do not have a long time series, we only use data from December 2022.

2.2 Biodiversity Risk Exposures Over Time

While we can only construct the survey- and holdings-based measures of biodiversity risk exposures at one point in time, the availability of historical 10-K statements allows us to construct a time series of firms' self-reported exposures to biodiversity risks.

[9] Specifically, Automobiles & Components (GICS code 2510), Consumer Durables & Apparel (GICS code 2520), and Household & Personal Products (GICS code 3030) are pooled into "Auto, Durables and Household Products". Consumer Services (GICS code 2530), Retailing (GICS code 2550), and Food & Staples Retailing (GICS code 3010) are pooled into "Consumer Services and Retailing". Banks (GICS code 4010) and Diversified Financials (GICS code 4020) are pooled into "Banks and Diversified Financials". Software & Services (GICS code 4510), Technology Hardware & Equipment (GICS code 4520), Semiconductors & Semiconductor Equipment (GICS code 4530), Telecommunication Services (GICS code 5010), and Media & Entertainment (GICS code 5020) are pooled into "IT and Communication Services." We decided to consolidate the 24 GICS industries to keep the survey interface manageable, in particular on mobile devices.

Figure 4: 10K-Based Biodiversity Scores Over Time



Note: Average 10K-Biodiversity-Count Score (solid line), 10K-Biodiversity-Negative Score (dot line), and 10K-Biodiversity-Regulation Score (dash line) over 2001 to 2020. The average scores are computed as the simple average of scores for all firms in each period.

Figure 4 shows our three 10K-based biodiversity risk exposure measures between 2001 and 2020, averaged across all firms in each period. Across all firms, self-reported biodiversity risk exposures have generally been growing over time, from about 1% of firms mentioning biodiversity-related terms in the early 2000s, to a peak of almost 5% of firms in 2018. This increase is largely driven by a corresponding increase in the number of mentions of biodiversity regulation risks. Consistent with this, the sentiment with which firms discuss biodiversity-related issues has declined over time.

2.3 Biodiversity Risk Exposures Across Industries

In this section, we compare the biodiversity risk exposures of different industries across our various measures. For this analysis, we aggregate the 10K-based firm-level exposure measures to the industry level by calculating the value-weighted average of the firm-level scores. Table 3 reports the cross-industry correlations of biodiversity exposures according to the different measures. We use 10-K statements in 2019 to do the cross-sectional comparison. The table highlights that our six industry-level measures of biodiversity risk exposures are substantially correlated: industries that are assessed to have high biodiversity risk exposures on one measure also have high exposures using the other measures.

Panel A of Figure 5 shows biodiversity risk exposures of different industries in 2019. To construct this figure, we first rank each industry from least exposed (rank = 1) to most

Table 3: Industry-level Correlations of Biodiversity Scores

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
10k-based Biodiversity Scores								
(1) 10k:Negative	1.00							
(2) 10k:Count	0.77	1.00						
(3) 10k:Regulation	0.93	0.88	1.00					
Survey-based Biodiversity Scores								
(4) Survey: Transition	0.50	0.57	0.57	1.00				
(5) Survey: Physical	0.21	0.27	0.24	0.82	1.00			
(6) Survey: Average	0.37	0.44	0.42	0.95	0.96	1.00		
Holding-based Biodiversity Scores								
(7) Holding	0.48	0.25	0.33	0.29	0.00	0.15	1.00	
Climate Exposure Scores								
(8) Quantity-based Climate Exposure	−0.18	−0.12	−0.06	−0.33	−0.13	−0.23	−0.25	1.00

Note: Industry-level Pearson correlations of 10K-based, Survey-based, Holding-based Biodiversity Scores, and Quantity-based Climate Score. The 10K-based Biodiversity Scores use data from 2019. Survey-based Scores use data in Q1 2023. Holding-based Score use data from Q4 2022. The Quantity-based Climate Score is computed with data from 2015 to 2019 inclusive.

exposed (rank = 24) and then average the ranks across our six measures.[10] The sectors with the highest average biodiversity risk exposures are energy, utilities, and real estate, while firms in the semiconductor, software, and communication services sectors are least exposed to biodiversity risks. Panel B of Figure 5 separately shows physical and transition risk exposures across industries as elicited in our survey.[11] Our survey participants perceive distinct heterogeneities among industries in terms of their biodiversity risk exposures: industries that are perceived to be exposed to physical biodiversity risks are not necessarily the same as industries that are perceived to be exposed to transition biodiversity risks.

To better understand the observed variation in biodiversity risk exposures across industries, we next consider the top industries in terms of average risk exposures and discuss the ways in which biodiversity risks affect those industries. To help with these interpretations, Appendix Figure A.2 provides word clouds with the terms that are most frequently mentioned in biodiversity-related sentences extracted from 10-K statements for each industry, with term sizes proportional to their frequency.[12] Appendix Figure A.3 shows the biodiversity risk exposure disaggregated to 6-digit GICS industry codes.

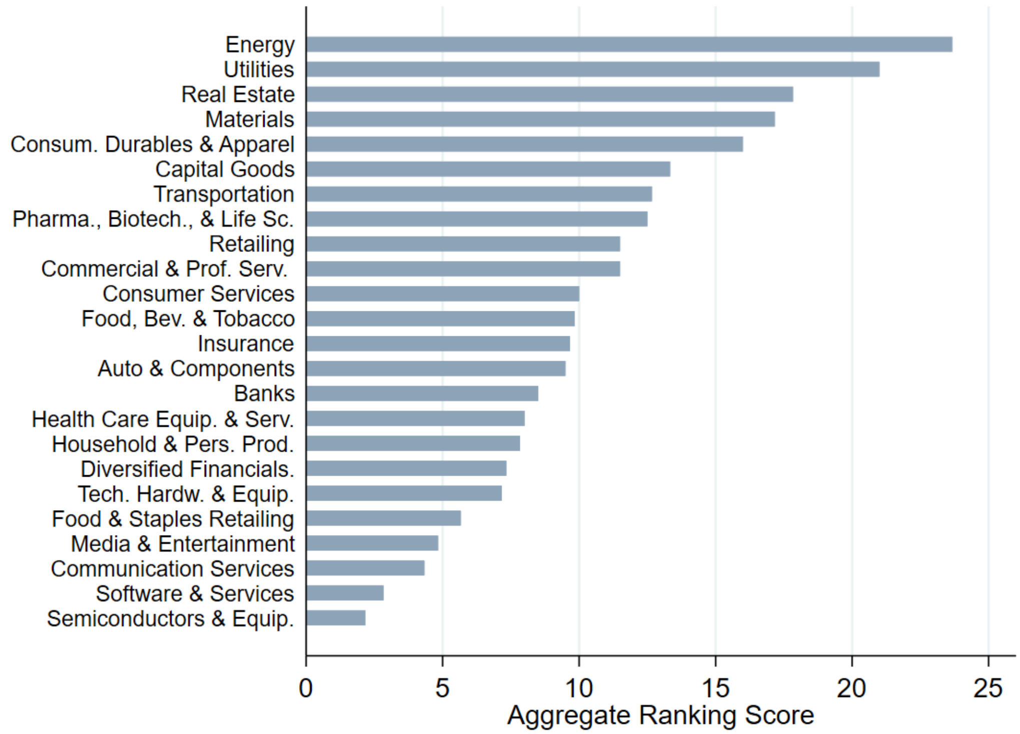
[10] Appendix Figures A.1a, A.1b, A.1c, and A.1d, and Appendix Table A.5 show the industry-level exposure measures separately for each of our various measures.

[11] Appendix Table A.6 shows the correlations of average industry rankings across different groups of survey respondents. The rankings are similar across subgroups, with the correlation ranging from 0.82 to 0.99. For example, the pairwise correlations between industry rankings reported by academics, private-sector employees, and public-sector employees are above 0.95.

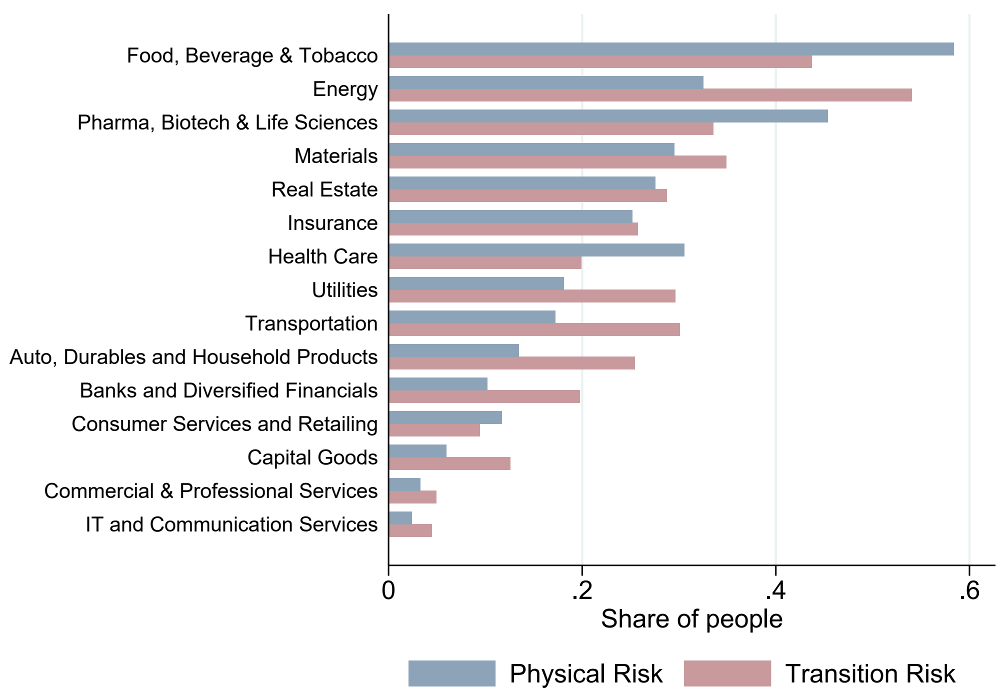
[12] To plot the word cloud, we extract biodiversity sentences using the same Biodiversity Dictionary for companies within each sector and aggregate these sentences into a "Biodiversity Vocabulary", which amounts to the list of unique terms and the associated frequency with which each term appears.

Figure 5: Industry-Level Biodiversity Risk Exposure

(a) Aggregate Score



(b) Survey-Based Score



Note: Panel A shows the average industry exposure ranking based on the simple average of six biodiversity risk measures in 2019. Panel B shows physical and transition risk exposures measured by survey responses.

Energy Sector. Our survey respondents assessed firms in the energy sector to have the highest biodiversity transition risk due to the potential impact of energy firms' operations on biodiversity. For instance, oil spills and habitat destruction during drilling activities can lead to the loss of species and ecosystem services, and entail substantial reputational and legal risks. The industry also faces regulatory risks, as governments introduce stricter environmental regulations and guidelines to prevent further biodiversity loss. Examples of firms in the energy sector describing such biodiversity risk exposures include:

> If one of our LNG terminals or pipelines may adversely affect a protected species or its habitat, we may be required to develop and follow a plan to avoid those impacts. [CHENIERE ENERGY INC]

> A critical habitat designation could result in further material restrictions on federal land use or on private land use and could delay or prohibit land access or development. [EARTHSTONE ENERGY INC]

Utilities. Firms in the utility sector are affected by both physical and transition risks. Physical risks matter, for example, when the degradation of watersheds affects water quality and availability, which in turn impacts water utility operations. On the transition risk side, regulations and laws on species and habitat protection may limit utility firms' operations, as shown in Panel B of Appendix Figure A.2. Besides, regulations on waste discharges, such as the Clean Water Act, elevate utility firms' costs, especially those in water utilities (see Appendix Figure A.3).

Interestingly, firms producing renewable electricity, which are often considered to be clean and potential winners of a climate transition, have the most substantial negative biodiversity risk exposure among firms in the utilities sector. This is because the construction of their wind, solar, and natural gas-fired power generation facilities requires substantial land and thus is subject to various land-use regulations to protect biodiversity. In addition, various regulations affect specific renewable energy sources: regulations on the protection of fish influences the development of hydropower projects, while regulations on the unintentional killing of migratory birds affect the development of wind farms.

> Our ability to meet the existing and future water demands of our customers depends on an adequate supply of water. Drought, governmental restrictions, overuse of sources of water, the protection of threatened species or habitats or other factors may limit the availability of ground and surface water. [American Water Works Company, Inc.]

> The Company is also subject to laws regarding the protection of wildlife, including migratory birds, eagles, threatened and endangered species. Federal and state environmental laws have historically become more stringent over time, although this trend could change in the future. [Clearway Energy, Inc.]

Real Estate. The real estate industry is exposed to biodiversity risks in various ways. For example, developments in areas with high biodiversity might face restrictions or require mitigation measures to minimize habitat destruction, adding costs and delays to projects.

> The sale or development of properties may also be restricted due to environmental concerns, the protection of endangered species, or the protection of wetlands. [ST JOE CO]

Materials. Materials industries, such as mining, timber, and construction, face a variety of biodiversity risks. Appendix Figure A.3 shows that Paper & Forest Products, Construction Materials and Metal Mining subsectors have particularly high biodiversity risks. Physical risks can impact the availability and quality of raw materials, such as timber from deforestation. In addition, regulations and legal and reputation risks represent additional exposures for this industry. Examples of firms in the materials sector describing their biodiversity risk exposures include:

> Federal and state requirements to protect habitat for threatened and endangered species have imposed restrictions on timber harvest on some of our timberlands, and these protections may be expanded in ways that further affect our operations. These actions may increase our operating costs; further restrict timber harvests or reduce available acres; and adversely affect supply and demand more broadly across our markets. [POPE RESOURCES LTD PARTNERSHIP]

> In addition, the Company's existing mining operations may become subject to additional environmental control and mitigation requirements if applicable federal, state and local laws and regulations governing environmental protection, land use and species protection are amended or become more stringent in the future. [STILLWATER MINING CO]

Pharma and Biotech. The Pharmaceuticals, Biotechnology & Life Sciences sector is exposed to substantial physical biodiversity risks. For example, in the last 40 years, about 60% of all new chemical entities in the field of antibacterials were based on or derived from natural products (Newman and Cragg, 2020). Biotechnology companies establish natural product libraries of microorganisms retrieved from soil, plant, and marine sources for drug discovery. Biodiversity loss therefore reduces potential pharmaceutical development options. Examples of firms in this sector describing their biodiversity risk exposures include:

> We focus on the use of biodiversity as a means of natural product drug discovery, while also using traditional chemical discovery and development techniques. [CUBIST PHARMACEUTICALS INC]

> [W]e believe the millions of microorganisms in each soil sample provide us with an almost limitless resource for continuing to create new and targeted libraries of natural product chemical diversity for drug discovery. [Abraxis BioScience Inc]

> Access to large libraries of highly diverse molecular structures is an important aspect of our drug discovery efforts. [...] This library includes [. . .] a natural product collection of independent samples derived from microbial, plant and marine sources. [TULARIK INC]

Capital Goods. Various Capital Goods companies are exposed to biodiversity risks that can impact their operations. Firms that supply building materials are exposed to both physical and transition risks. Deforestation and desertification can raise the cost and reduce the availability of wood, the crucial raw material for these firms. Besides, as consumer awareness about biodiversity grows, there is a shift of preference toward eco-friendly products. Consequently, there is an increased demand for sustainable products, and firms have to adapt their product offerings to meet these changing preferences. Furthermore, distributors' operations are subject to transition risks, such as stricter regulations. For example, regulations governing the use of chemical refrigerants require distributors to retrofit their containers, and biodiversity concerns can impact the use of construction materials in dry containers, both of which will incur large retrofitting expenses. Finally, industrial and construction companies must comply with environmental protection and waste disposal regulations, which can increase their operating costs.

> As another example, many consumers demand certified sustainably harvested wood products as concerns about deforestation have become more prevalent. [JELD-WEN Holding, Inc.]

> Our marine infrastructure construction, salvage, demolition, dredging and dredge material disposal activities are subject to stringent and complex federal, state, and local laws and regulations governing environmental protection, including air emissions, water quality, solid waste management, marine and bird species and their habitats, and wetlands. [Orion Marine Group Inc]

> The State also seeks declarations under MERLA that 3M is responsible for all damages the State may suffer in the future for injuries to natural resources from releases of PFCs into the environment, and under MWPCA that 3M is responsible for compensation for future loss or destruction of fish, aquatic life, and other damages. [3M CO]

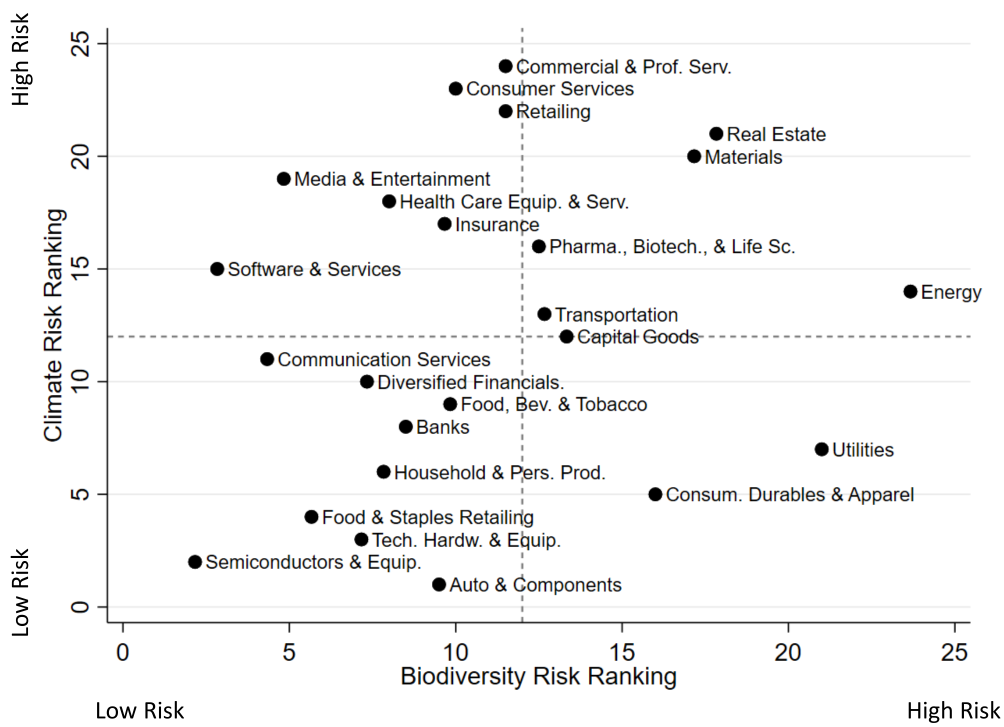
Transportation. Marine transportation firms frequently mention biodiversity in their 10-K statements. Regulations related to the protection of marine species and their habitats can impact the speed and route of vessels, leading to additional costs. Besides, regulations aimed at reducing marine pollution can impact the type of fuels used by ships, which may require the installation of new equipment and result in additional operating costs. Lastly, regulations related to the management of ballast water may require companies to clean their hulls to prevent the spread of invasive species.

> Protection of endangered and threatened species may include restrictions on the speed of vessels in certain ocean waters and may require the Company to change the routes of the Company's vessels during particular periods. [...] The reduced speed and special routing along the Atlantic Coast results in the use of additional fuel, which affects the Company's results of operations. [SEACOR HOLDINGS]

2.4 Climate Risk Exposures vs. Biodiversity Risk Exposures

Just like aggregate biodiversity news is distinct from aggregate climate news (see Section 1.3), firm- and industry-level exposures to biodiversity risk are distinct from climate risk exposures. The bottom row of Table 3 shows our measures of biodiversity risk exposure at the industry level are related to the "quantity-based climate exposure" measure developed in Alekseev et al. (2022). This measure identifies industries that investors buy (lower score) and sell (higher score) in response to changes in their beliefs about climate change, and Alekseev et al. (2022) show that long-short portfolios based on this exposure characteristic have the ability to hedge news about climate risks. Figure 6 shows a corresponding scatter plot, where biodiversity risk exposure is measured by the average ranking across our six biodiversity risk measures.

Figure 6: Industry Ranking by Biodiversity Risk and Climate Risk



Note: Scatterplot of industry biodiversity risk ranking and climate risk ranking. The biodiversity risk exposure is measured by the average ranking across the six biodiversity risk measures, and the climate risk exposure is measured by the pooled quantity-based climate exposure. Both measures use data in 2019.

Industries with high biodiversity risk exposures are broadly distinct from industries with high climate risk exposures. There are several reasons for this. First, an industry may be highly exposed to biodiversity risk because its operations are dependent on particular ecosystems or species that are not necessarily affected by climate change. Second, from a regulatory perspective, some industries might have a more significant direct impact on ecosystems and habitats rather than contributing to climate change. As a result, they would be more affected by biodiversity regulation than climate regulation.

As an example, the mining and extraction industries can cause severe damage to local ecosystems through habitat destruction, water pollution, and the introduction of invasive species, making them more exposed to biodiversity transition risk than climate risk. Similarly, as described above, biodiversity regulation provides challenges for renewable energy firms, while climate regulation provides many opportunities.

3 Regional Measures of Biodiversity Risk Exposures

In the preceding sections, we focused on measuring variation in biodiversity risk exposures across different firms and industries in the United States. In this section, we quantify the *spatial* variation in biodiversity risk across different U.S. counties. We explore two ways to capture each county's exposure to biodiversity risks. Based on our prior insight that industries are differentially exposed to this risk, we first study the risks due to the industry composition in each country, where we measure industry composition through employment and GDP shares. Second, we construct two ecology-based measures built from geographical data, such as the presence of protected areas and endangered species in the county.

Employment-Based Biodiversity Score. We use employment data from the U.S. Census Bureau's County Business Pattern (CBP) to capture county-level variation in industry composition. We then construct a measure of a county's biodiversity risk as the employment-weighted average of the biodiversity measures of the industries operating in the county.[13] Panel A of Figure 7 shows the distribution of Employment-Based Biodiversity Score in 2020.

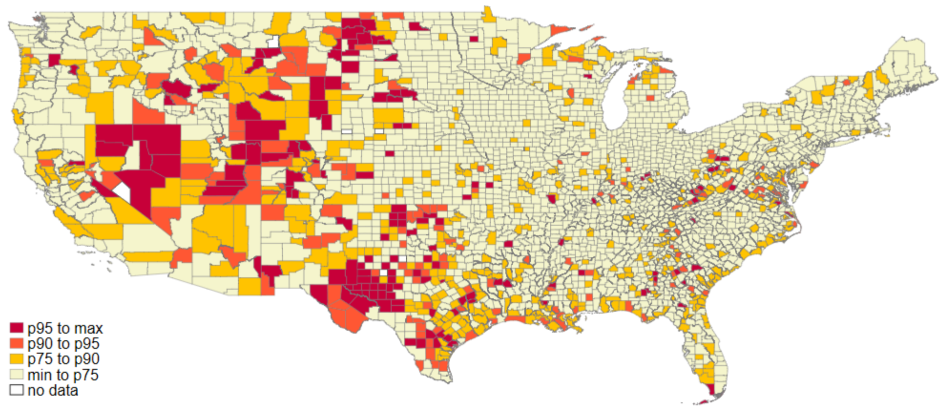
GDP-Based Biodiversity Score. A second industry-based biodiversity risk measure at the county level weights industry-level biodiversity scores by the GDP of each industry in the county, using data from the Bureau of Economic Analysis (BEA).[14] Panel B of Figure 7 displays the distribution of GDP-Based Biodiversity Scores in 2020. Figure 7 shows that counties located in Texas, Wyoming, and North Dakota exhibit the highest levels of industry-based biodiversity risk, potentially due to their significant energy and materials industries, such as oil and gas production and mining, as shown in Appendix Figure A.6.

[13] We map 2-digit NAICS industry codes from the CBP with 4-digit GICS industry codes using the crosswalk in Appendix Table A.8 and merge this data with industry biodiversity scores, which are calculated as the average of six biodiversity measures.

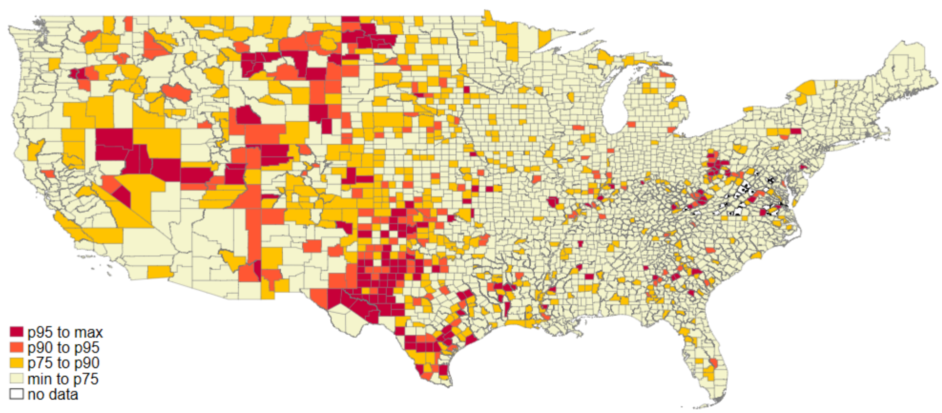
[14] The BEA provides annual GDP information by industry for 19 industries with two-digit NAICS codes. We use the crosswalk in Appendix Table A.8 to match NAICS and GICS industries.

Figure 7: Spatial Distribution of Industry-Based Measures of Biodiversity Risk Exposure

(a) Employment-Based



(b) GDP-Based



Note: Spatial Distribution of Industry-Based Measures of Biodiversity Risk Exposure in 2020. "Employment-Based Score" is computed as the average industry biodiversity scores weighted by the number of people employed in each industry (Data source: County Business Pattern). "GDP-Based Score" is computed as the average industry biodiversity scores weighted by the GDP of each industry (Data source: Bureau of Economic Analysis). Regions with darker colors have a higher biodiversity risk.

Protected Area Score. We construct our first ecology-based measure of local biodiversity risk exposure based on the Protected Areas Database of the United States PAD-US, which provides a national inventory of terrestrial and marine protected areas that are dedicated to the preservation of biodiversity and to other natural, recreation, and cultural uses. We focus on the terrestrial areas that are classified as managed for biodiversity protection and compute the Protected Area Score as the share of protected area (% of total area).[15] Panel A of Figure 8 shows the distribution of the Protected Area Score. Most protected areas are situated in the Western United States, which are often characterized by dense forests.

[15]We focus on Status 1 ("managed for biodiversity–disturbance events proceed or are mimicked") and Status 2 ("managed for biodiversity–disturbance events suppressed"), and use the 2022 version of the data.

Endangered Species Score. The second set of ecology-based measures is based on the IUCN Red List of Threatened Species, a comprehensive inventory of the conservation status of plant and animal species worldwide.[16] We consider vulnerable, endangered, or critically endangered species on the IUCN Red List as threatened species and include species of all taxons. We compute the Endangered Species Score as the number of all endangered species divided by the number of all species for each county. Panel B of Figure 8 displays the distribution of the baseline Endangered Species Score for all species; due to the high prevalence of endangered marine species, it is highest in coastal counties. To account for the differences in ecosystems due to county location, Appendix Figure A.5 also shows an Endangered Species Score separately for marine species, terrestrial species, and freshwater species.

Biodiversity Risk Exposures Across U.S. Counties. We next compare the county-level biodiversity risk exposures across various measures. Table 4 reports the correlations between the 2020 industry-based biodiversity measures and the 2022 ecology-based biodiversity measure (GDP and employment data in 2022 are not available yet). Positive correlations are observed within both industry-based and ecology-based measures, while no strong correlations are observed across these two groups.

Table 4: Correlation Across County-Level Biodiversity Risk Measures

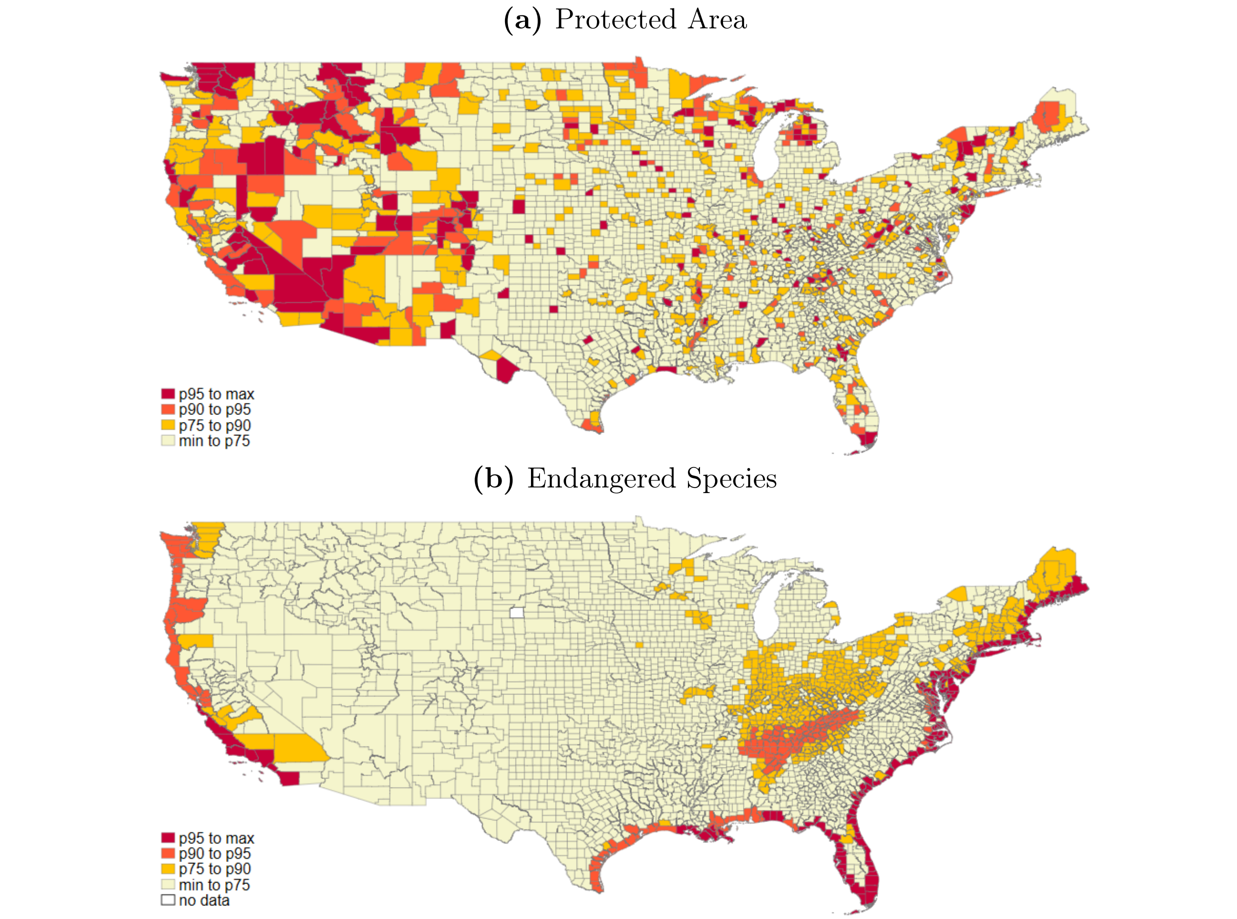
	(1)	(2)	(3)	(4)
Industry Measures of Biodiversity Risk				
(1) Employment-Based Biodiversity Score	1.00			
(2) GDP-Based Biodiversity Score	0.57	1.00		
Ecology Measures of Biodiversity Risk				
(3) Protected Area Score	0.05	0.00	1.00	
(4) Endangered Species Score	−0.09	−0.25	0.11	1.00

Note: Correlation across measures of county-level biodiversity risk exposure in the United States. Industry-based measures are based on data in 2020, and ecology-based measures are based on data in 2022.

The relationships between ecology-based and industry-based measures are nuanced, and the right measure of biodiversity risk exposure depends on the particular application. For example, counties with more protected areas and endangered species may face higher regulatory restrictions on firms' operations, which could induce firms in industries with a larger effect on biodiversity, such as energy and material companies, to locate elsewhere.

[16] Species distribution data is comprised of polygons representing the geographical regions where specific species can be found. We employ spatial join (through the GeoPandas package in Python) to determine the overlap between the habitats of various species and the borders of counties. For instance, if the designated area for a species intersects with three different counties, it is inferred that the species inhabits all three of these counties. We use the 2022 version of the data.

Figure 8: Spatial Distribution of Ecology-Based Measures of Biodiversity Risk Exposure



Note: Spatial Distribution of Ecology-Based Measures of Biodiversity Risk Exposure in 2022. "Protected Area Score" is computed as the share of the protected area (% of total area) (Data source: Protected Areas Database of the United States). "Endangered Species Score" is computed as the share of endangered species (% of all species) (Data source: IUCN Red List of Threatened Species). Regions with darker colors have a higher biodiversity risk.

Global Biodiversity Risk Exposures. To inform global patterns of biodiversity risk exposure, Appendix A.4.4 introduces two country-level measures of risk exposures based on IMF reports and endangered species data. While we do not explore these data in detail in this paper, we make these measures available on www.biodiversityrisk.org. In line with the survey results, we find that countries located in Asia and the rest of the world exhibit a higher proportion of endangered species and focus more on biodiversity issues in their interactions with the IMF. One potential avenue for future research is to examine whether biodiversity risk is incorporated into the pricing of sovereign bonds.

4 The Pricing of Biodiversity Risk

A recent body of research in economics and finance has documented that for the last decade—starting around 2010—various measures of firm- and county-level exposures to climate risk have been priced in asset markets (e.g., Bolton and Kacperczyk, 2021; Engle et al., 2020; Alekseev et al., 2022; Acharya et al., 2022). In this section, we explore whether biodiversity risk—a category of risk that has attracted the attention of market participants relatively more recently—appears to affect prices in equity and municipal bond markets.

4.1 Pricing in Equity Markets

We first combine our quantitative measures of aggregate news about biodiversity risk with our industry-level measures of biodiversity risk exposures to ask whether biodiversity risks are currently incorporated into equity prices.

We begin by forming portfolios of industries sorted by their biodiversity risk exposures. If biodiversity risk is priced in asset markets—and if our measures of exposure to this risk are correct—we would expect the price of these portfolios to move with the arrival of (aggregate) news about biodiversity risks. For example, when negative biodiversity news arrives, the valuations of highly exposed industries should drop, while the valuations of less exposed industries should drop by less (or even increase). Put differently, if biodiversity risks are priced, we should expect the return to this biodiversity risk-sorted portfolio to covary with the aggregate biodiversity risk news series: it should behave like a *hedging portfolio*.

Note that researchers sometimes refer to the presence of risk premia when asking whether a risk is "priced." That language references to the compensation for risk required by investors, which has as a necessary (but not sufficient) condition that prices respond to risk realizations. We focus on the latter pattern—asking whether asset prices display a beta with respect to biodiversity risk—because estimating risk premia would require a much longer time series.

To implement our test, we measure innovations in biodiversity news, Bio_t, by averaging the daily values of our aggregate NYT-Biodiversity News Index within each month and then computing values of Bio_t as residuals from a monthly AR(1) model. We then construct portfolios that go long firms with low biodiversity risk exposures—i.e., firms that are not affected or might even benefit from realizations of biodiversity risks—and short firms with high biodiversity risk exposures, those firms negatively affected by biodiversity risk realizations.[17] We construct six such portfolios using the three 10K-based biodiversity scores, the two survey-based scores, and the holding-based score. We construct all portfolios using exposure measures at the industry level, aggregating the firm-level 10K-based scores to the industry level by taking the value-weighted average of the firm-level values.[18]

[17]Since all exposure measures were designed such that higher values are associated with higher biodiversity risk exposures, the portfolios would go long industries with low scores and short industries with high scores.

[18]While our baseline 10k-based hedge portfolios are constructed using exposure data aggregated to the industry level, the underlying risk exposures are available at the firm level. In a robustness test, we also construct long-short portfolios at the firm level. For example, we form portfolios that go long all the stocks that do not mention biodiversity or biodiversity regulation and go short those that mention them. Both

To determine the portfolio weight of each industry, we take two approaches. In our main rankings-based approach, the portfolio's position in each industry is the industry's biodiversity score percentile in the industry distribution, minus 50. For example, the portfolios take a long position of 50 in the industry with the lowest biodiversity score and short a position of -50 in the industry with the highest biodiversity score. The industry with the median biodiversity score is not held, and half of the industries are in a long position and half are in a short position. We show that our main findings are robust to a second approach that holds positions in each industry as the cross-sectionally demeaned biodiversity scores in that year, taking long positions for industries with below-average scores (and risk exposures), and short positions for industries with above-average scores. We consider both separate portfolios for each biodiversity exposure measure as well as a portfolio that first averages the industry weights across the six measures. In each period, we compute the excess returns of each portfolio by subtracting the risk-free rate from the value-weighted industry returns.

Figure 9 reports the correlations between the various biodiversity hedging portfolios and innovations in the biodiversity risk index. We also include a portfolio that uses the average values of the alternative approach to creating industry weights described in the previous paragraph. We focus on the period after 2010, since we do not expect markets to price biodiversity risk before that time.[19] All the correlations are positive, with magnitudes from around 0.09 to 0.2. The largest correlations are achieved by the portfolios sorted on the average across our six industry-level biodiversity risk exposure scores, presumably because this averaging leads to more precise estimates of industry exposures. Quantitatively, the observed correlations are comparable to those obtained by climate hedging portfolios when evaluated against aggregate climate news (Engle et al., 2020; Alekseev et al., 2022).

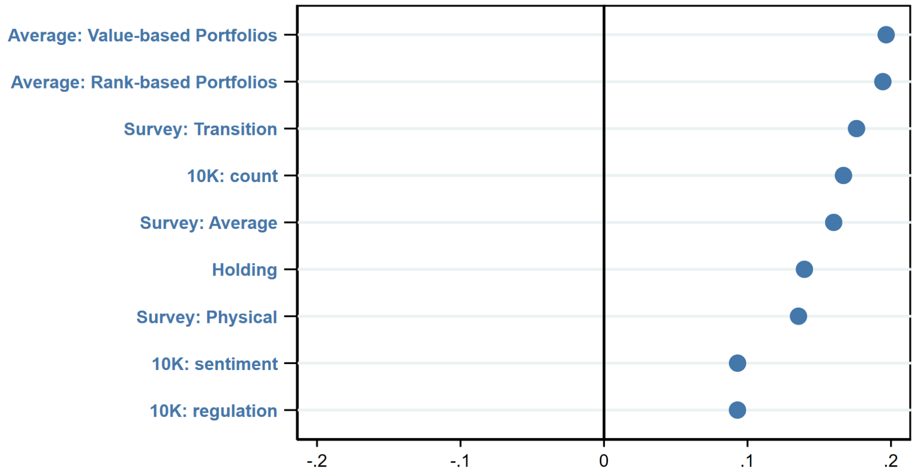
A natural question is whether our measures of biodiversity risk exposure are simply recasting information from other firm characteristics. To study this, we investigate whether using other characteristics would yield similarly good hedging portfolios for aggregate news as the ones based on measures of biodiversity risk exposure.

In comparing our measures of exposures with other characteristics, one important consideration is that, in general, we do not have a clear prior on whether the various characteristics (e.g., firm size, book to market, etc.) should be associated with a high or low exposure to biodiversity risk. For example, we do not know ex-ante if a portfolio that goes long value companies and short growth companies (HML) should covary positively or negatively with biodiversity risk. Building a hedging portfolio using alternative characteristics therefore requires estimating the sign of the relationship between the biodiversity beta and the characteristic using a mimicking portfolio approach (as in Engle et al., 2020; Alekseev et al.,

portfolios are value-weighted. For the 10K-Biodiversity-Negative Score, we multiply the score by the market capitalization and use the product as the weight to construct a long-short portfolio that goes long firms that express more positive sentiment, goes short those that express negative concerns, and has no position in neutral sentiment. We find that correlations of biodiversity risk with portfolios based on the 10k-based exposure measures at the firm level are similar (though perhaps a little smaller) to the correlations with portfolios based on 10k-based exposure measures at the industry level (see Panel A of Appendix Figure A.7).

[19] Appendix Figure A.4 shows a corresponding graph for the period 2000-2009. Only two out of six measures have positive correlations, and the correlation of the average portfolio is small and negative.

Figure 9: Biodiversity Hedge Performance of Various Portfolios



Note: Dot plot of monthly return correlations for various biodiversity hedge portfolios with AR(1) innovations of NYT-Biodiversity Risk Index using data from 2010 to 2020.

2022). The mimicking portfolio approach uses historical data to combine a pre-determined set of assets into a portfolio that is maximally correlated with a given biodiversity shock. To obtain the mimicking portfolios, we estimate the following regression:

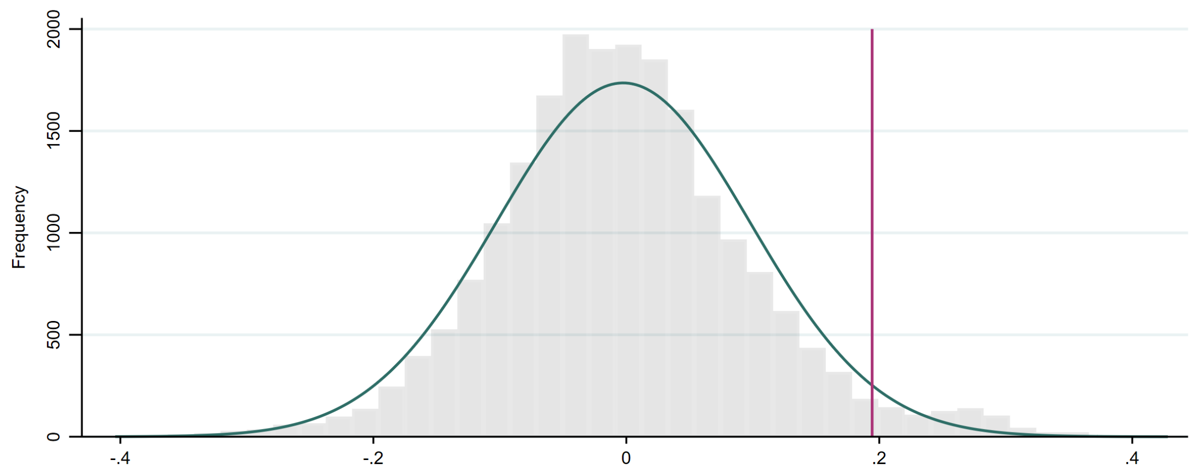
$$Bio_t = wR_t + \epsilon_{c,t}$$

where Bio_t denotes the (mean zero) biodiversity hedge target in month t, w is a vector of N portfolio weights, and R_t is a vector of demeaned excess returns. The portfolio weights are estimated each month using a five-year rolling window. When the vector R_t contains one characteristic-sorted return only (e.g., HML), the weight w represents the relation between that characteristic and the biodiversity beta. For example, if we build a hedging portfolio using HML and estimate $w > 0$, then we expect value stocks to hedge biodiversity risk going forward; if $w < 0$, we expect growth stocks to hedge this risk.

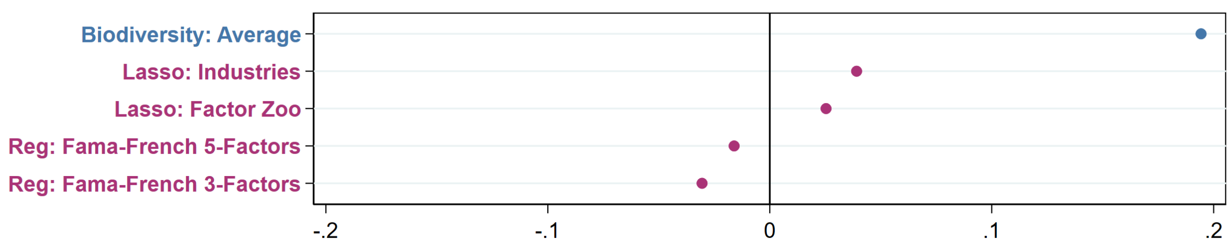
Panel A of Figure 10 shows the histogram of the out-of-sample correlation of mimicking portfolios built using the 207 characteristics obtained from Chen and Zimmermann (2022). The red bar represents the portfolio built using our average biodiversity risk measure. The light grey portfolios represent mimicking portfolios built using each of the 207 characteristics individually and their pairwise combinations (21,321 portfolios in total). Of course, there is a large amount of sampling error, so that among the many mimicking portfolios, some correlate more and some less with biodiversity news. Importantly, our economically motivated measure provides a positive hedging performance that ends up in the 95th percentile of the distribution of correlations in this set of characteristics. Panel B of Figure 10 shows the monthly out-of-sample return correlations for the portfolio built using the average biodiversity risk measure, and four mimicking portfolios built with the Fama French Three Factors (Market, SMB, and HML), the Fama French Five Factors (Market, SMB, HML, RMW, and CMA), and with

Figure 10: Hedging Biodiversity Risk Using the Factor Zoo

(a) Correlation Distribution



(b) Hedging Performance



Note: Panel A shows the histogram of the out-of-sample correlations with AR(1) innovations of the NYT-Biodiversity Risk Index using data from 2010 to 2020. The grey bars represent mimicking portfolios built using each of the 207 characteristics individually and their pairwise combinations. The red bar is the hedging performance achieved by a portfolio that is sorted on the average of all biodiversity risk measures. Panel B shows the dot plot of monthly out-of-sample return correlations for various hedge portfolios with AR(1) innovations of the NYT-Biodiversity Risk Index using data from 2010 to 2020. Each dot represents one correlation coefficient. The portfolio with a blue label is built based on the average of six biodiversity risk measures and using the ranking-based approach. The portfolios with red labels are mimicking portfolios constructed with 24 industries, 207 characteristics, Fama-French Five Factors, and Fama-French Three Factors, and estimated each month using a five-year rolling window.

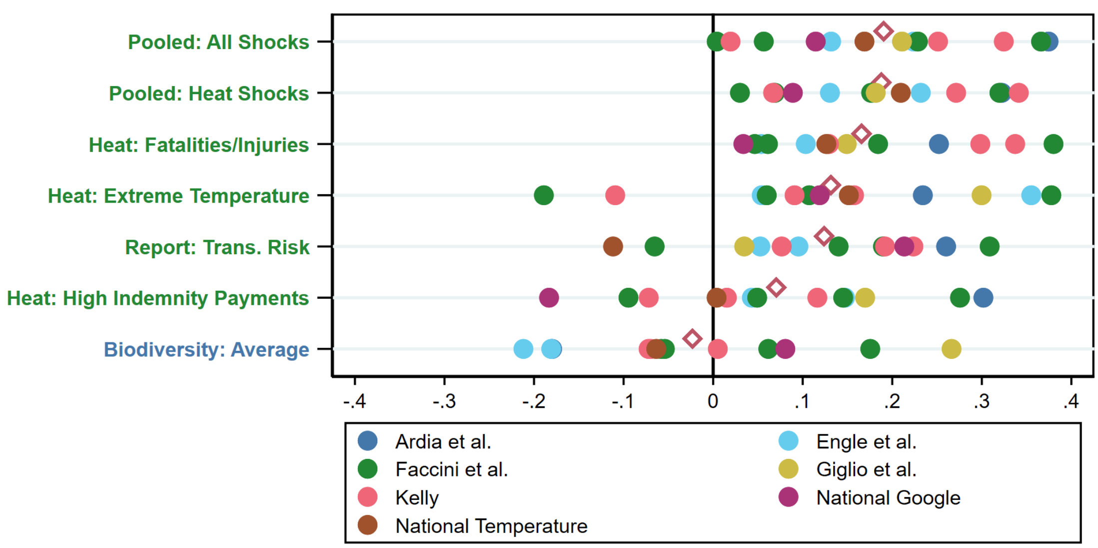
all 207 characteristics and all 24 industries, each selected by a LASSO to avoid over-fitting. The portfolio built on the average biodiversity exposure measure has the highest correlation with innovations in the NYT-Biodiversity Risk Index.

Finally, in Appendix A.4.3 we develop an alternative way to statistically compare the hedging performance of our biodiversity exposure measures, which are motivated a priori, with that of the 207 stock characteristics. The test explicitly takes into account the multiple testing problem associated with the 207 characteristics, which are not economically motivated—i.e., the fact that among the "characteristics zoo", we would expect some to be correlated with biodiversity risk well just by chance. To adjust for multiple testing, we use the method of Benjamini and Hochberg (1995). We find that the good hedging performance of some of the 207 characteristics is indeed due to chance: none of them is significant after adjusting for the multiple testing problem.

Overall, we find that the returns of portfolios that are sorted on various measures of biodiversity risk exposure covary positively with realizations of biodiversity news. These findings suggest both that our measures of risk and exposure are reasonable, and that biodiversity risks are already priced in equity markets.

Hedging Biodiversity Risk vs. Climate Risk. To further explore the similarities and differences between climate and biodiversity risk, we compute the monthly correlations of biodiversity and climate hedge portfolios against climate risk realizations. For the biodiversity hedge portfolio, we use the one constructed with the average of our six biodiversity measures. We compare the climate hedge performance against that of a range of quantity-based climate hedge portfolios developed in Alekseev et al. (2022), and study a range of climate news series as potential hedge targets. Figure 11 shows that, in general, portfolios designed to hedge climate risks perform better than biodiversity hedge portfolios, which, on average, have zero correlation with realizations of news about climate risk.

Figure 11: Climate Hedge Performance of Various Portfolios



Note: Dot plot of monthly return correlations for various hedge portfolios with AR(1) innovations of various climate risk Index using data from 2015 to 2020. Each dot represents one correlation coefficient. Different colors represent different groups of climate news series. The dark blue dot is the Media Climate Change Concerns index by Ardia et al. (2020), light blue dots are Wall Street Journal and Crimson Hexagon Negative News climate news indices by Engle et al. (2020), green dots are indices by Faccini et al. (2021), the yellow dot is the NYT-Climate News Index constructed in Section 1, pink dots are general, physical, and transition risks indices by Kelly (2021), the violet dot is the national Google search index, and the red dot is the national temperature deviation index. See detailed discussion of these indices in Alekseev et al. (2022). The red rhombus shows the unweighted average among all correlations, and portfolios are sorted top-to-down by this value. The portfolios with green labels are climate hedging portfolios while the portfolio with the blue label is formed with the average biodiversity measures using the ranking-based approach.

4.2 Pricing in Municipal Bond Markets

We next ask whether spatial variation in various biodiversity risk exposures is currently priced in municipal bond markets. To conduct this analysis, we form long-short portfolios of municipal bonds sorted on various biodiversity risk exposures and test if the return of these risk-sorted portfolios covaries with the aggregate biodiversity risk news series.[20]

Unlike stocks, municipal bonds trade only infrequently. Therefore, we adopt the methodology in Auh et al. (2022) to construct monthly returns at the county level (see Appendix A.4.5 for details). We obtain monthly municipal bond returns for 1,386 counties, which we merge with data on biodiversity risk exposures to form portfolios using the ranking-based approach described in Section 4.1. We construct six such portfolios using two industry-based exposure measures, two ecology-based exposure measures, one average industry-based measure, and one average ecology-based measure.[21]

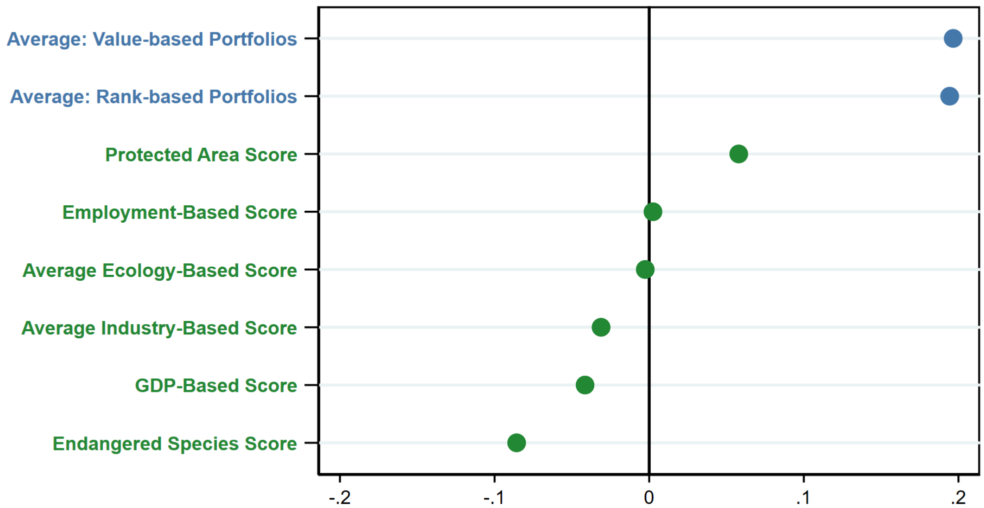
In Figure 12, rows with green labels show the correlations between the biodiversity news and the returns of characteristic-sorted municipal bond portfolios (rows with blue labels show correlations with the returns of characteristics-sorted equity portfolios from Section 4.1 for comparison). We find essentially no correlation, which is consistent with a range of interpretations: perhaps our exposure measures are not capturing what financial market participants are focusing on in terms of biodiversity risk exposures of municipal bonds; perhaps the illiquidity of the underlying bonds makes our return series problematic; or perhaps the biodiversity risk isn't priced in the municipal bond market.

Our baseline sample includes monthly municipal bond returns from 1,386 counties, but some counties' bonds have particularly infrequent trading. For example, at the 10th percentiles of county-months, we only have two municipal bonds traded in three transactions. To assess the robustness of our results in considering counties with more transactions—and thus more precisely estimated returns—we focus on counties with more frequent transactions and construct long-short portfolios using returns of counties with at least one bond traded each quarter (450 counties); at least 10 bonds traded each quarter (295 counties); at least 50 bonds traded each quarter (160 counties); and at least 100 bonds traded each quarter (96 counties). Panel B of Appendix Figure A.7 shows correlations similar to those in Figure 12 for variations of municipal portfolios constructed using the two average biodiversity measures. Across the different portfolios, higher trading frequencies have little effect on the overall hedge performance and we find no evidence of a robust correlation between portfolio returns and biodiversity news. This makes it less likely that the null-results observed above are due to the concerns described above with the return series data.

[20] Previous literature has found that municipal bond issuers located in counties that are more exposed to physical climate risks have higher borrowing cost (Painter, 2020; Goldsmith-Pinkham et al., 2021; Acharya et al., 2022). We do not explore how biodiversity risk exposures affect the initial yields of municipal bonds, since our key exposure measures are based on the industry composition in a county, which should directly affect yields in a way that would confound any interpretation of its relationship with risk exposures.

[21] To compute the average score, we first standardize all scores to the range between 0 and 1 and compute the average industry-based score as the simple average of employment-based and GDP-based scores, and the average ecology-based score as the simple average of protected area and endangered species scores.

Figure 12: Biodiversity Hedge Performance of Various Municipal Bond Portfolios



Note: Dot plot of monthly return correlations for various biodiversity hedge portfolios with AR(1) innovations of NYT-Biodiversity Risk Index using data from 2010 to 2020. Each dot represents one correlation coefficient. Green rows correspond to characteristic-sorted portfolios of municipal bonds, and blue rows to characteristic-sorted equity portfolios.

4.3 Survey Evidence on the Adequacy of Biodiversity Risk Pricing

While the previous section suggested that biodiversity risks are at least somewhat reflected in equity prices—with less conclusive evidence for the pricing in municipal bond markets—it is much less clear whether or not the current pricing of these risks is adequate to reflect the true underlying risks. Answering this question is particularly challenging, and would require taking a precise view of the exact nature of the risks and the ways they would affect the cash flows of different firms.

To provide some initial insights into this important question, we asked the respondents to our survey whether they believed that prices across a range of asset classes appropriately reflected biodiversity risks. Table 5 highlights that about half of all survey respondents believed that asset markets underpriced biodiversity risks across equity markets, commodity markets, sovereign debt markets, and real estate markets (about 35% of respondents had no particular views on the pricing of these risks, while fewer than 5% of respondents believed that these risks were overpriced). These responses are consistent across respondents from different institutions and locations. We also find that people who are worried about biodiversity are more likely to believe that asset markets have not yet priced biodiversity risks appropriately, while people with no concern think it is overpriced.

Table 5: Current pricing of biodiversity risks in asset markets

		Role			Location				Biodiversity Concern			
	Pooled	Academic Institution	Private Sector	Public Sector	North America	Europe	Asia	ROW	Very High	High	Low	No Concern
Stock Market (%)												
Not enough	48	43	53	61	45	53	60	69	71	53	30	6
Correct	17	23	11	15	18	17	13	23	11	26	33	23
Too much	3	3	5	3	5	1	2	0	2	2	8	29
No opinion	32	31	32	21	33	28	25	9	16	19	29	42
Commodity Market (%)												
Not enough	43	39	46	55	39	47	57	63	65	45	24	3
Correct	19	25	14	17	20	21	15	20	13	29	39	23
Too much	3	2	5	5	5	1	0	6	1	2	8	29
No opinion	35	35	35	22	36	30	28	11	20	24	29	45
Sovereign Debt Market (%)												
Not enough	43	39	44	58	41	48	50	60	65	45	29	3
Correct	14	20	10	8	16	13	12	9	6	23	33	19
Too much	2	2	2	4	2	1	2	6	0	2	3	26
No opinion	41	39	44	30	41	38	37	26	29	30	35	52
Real Estate Market(%)												
Not enough	46	42	48	61	45	51	53	54	66	51	32	3
Correct	16	22	12	9	17	15	13	20	10	23	32	29
Too much	2	1	3	3	2	2	0	3	0	1	5	26
No opinion	37	35	38	27	37	32	33	23	24	25	32	42

Note: Participants were asked: "To what extent do you think that physical or transition biodiversity risks are currently priced in the following asset markets?", where asset markets are either stock markets, real estate markets, commodity markets, or sovereign debt markets.

5 Conclusion

Biodiversity services play a fundamental role in the economy and risks stemming from biodiversity loss can affect firms through many channel. Yet, those risks can be difficult to quantify and study systematically. The goal of this paper is to introduce measures of aggregate biodiversity risk as well as measures of firms' and industries' exposures to these risks; to connect and validate these two; to study the pricing of biodiversity risks in financial markets; and to publicly release our biodiversity exposure measures at www.biodiversityrisk.org to facilitate more research on this important topic.

Given the complexity of biodiversity risk, our paper blends a number of different data sources: textual information, cross-sectional pricing information, and survey data. We employ a variety of methods that allow us to combine these different data sources and construct quantitative series that can be studied together. In addition, the measures we produce can be related to other ones explored in the previous literature, like the long list of firm "anomalies", and the vast literature on climate risks.

We view our work as providing a starting point for quantitative analyses of biodiversity risk. Many extensions and refinements could be pursued. Among them: an integrated study of the pricing of biodiversity risk across asset classes; a refinement of the different types of biodiversity risk (e.g., species vs. ecosystem diversity); and a more fundamental understanding of the interactions between biodiversity risk and climate risk.

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A.1 Tables

Table A.1: Correlation Across Measures of Aggregate Risk After 2010

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Biodiversity Risk Measures							
(1) NYT-Biodiversity News	1.00						
(2) Google-Biodiversity Attention	0.43	1.00					
Climate Risk Measures							
(3) NYT-Climate News	0.28	0.18	1.00				
(4) Faccini et al (2021): Internat. Summit	−0.21	−0.07	−0.08	1.00			
(5) Faccini et al (2021): Global Warming	−0.12	0.20	0.13	0.24	1.00		
(6) Faccini et al (2021): Natural Disaster	0.36	0.21	0.22	0.15	0.38	1.00	
(7) Faccini et al (2021): Narrative	−0.13	−0.21	−0.26	0.31	0.10	0.14	1.00

Note: Pairwise monthly correlation across biodiversity and climate risk measures. NYT-based and Google-based measures are based on data from 2010-2022, while Faccini et al (2021) indices use data from 2010-2020.

Table A.2: Example Answers From Open Text Survey Question

Role	Answer
Private Sector	I invest in early-stage climate tech companies, so I am constantly thinking about biodiversity risks and companies that are addressing those risks.
Private Sector	I co-run an investment fund in farmland and timberland, which are directly affected by these risks.
Private Sector	loss of key ecosystem services for agriculture and manufacturing.
Private Sector	Assessing project risks properly given biodiversity risks bring greater uncertainties that we have less foresight in factoring them into the overall viability of infrastructure projects.
Private Sector	I cover part of the energy sector so the physical risk is something we look at.
Private Sector	Yes, as a real estate investor.
Private Sector	Yes as a ESG stock analyst we are seeing an increased focus on biodiversity risk and policy action
Private Sector	More demand for consulting services on the matter
Private Sector	There are insufficient risk disclosures by borrowers and a lack of standard disclosures from which capital markets can appropriately assess and price risk.
Private Sector	Yes I work in Climate Risk for A Bank and biodiversity is something we are looking at now. While biodiversity risk is important to manage it should be done in consideration of economic challenges such as inflation & recession risk and we are in favor or a just transition especially as we operate in developing markets
Private Sector	Yes, companies are now considering biodiversity risks and asking for my expertise in this field more which is very encouraging, while helping companies change their practices with nature.
Private Sector	Regulatory risks related to biodiversity are chief drivers of long-term uncertainty in the energy markets in which I work.
Private Sector	There are insufficient risk disclosures by borrowers and a lack of standard disclosures from which capital markets can appropriately assess and price risk.
Private Sector	As working in the buy side, we are focusing more on impact investment to address ESG issues, including to moderate biodiversity risk
Private Sector	It definitely informs the kind of companies I negatively screen. We don't have an active biodiversity risk strategy; but I tend to negatively view companies that will cause harm to our environment form a long-term business sustainability perspective (as a VC)

Note: Participants were asked: Are there any particular ways in which biodiversity risks are important in your professional life?

Table A.2: Example Answers From Open Text Survey Question (cont.)

Role	Answer
Private Sector	Risk gets re-priced when recognition of those risks becomes generally understood. This raises the cost of capital for businesses which tends to be negative for capital assets in general, especially if its a "shock." This, combined with a re-pricing of negative externalities associated with activities leading to biodiversity loss creates uncertainty that investors and companies eventually need to confront. The confrontation can result in innovation or decline or both. All of this makes investment decisions much more difficult.
Private Sector	I am a hedge fund investor and find that companies well suited to address changes are overpriced, especially global stocks. The point is that there are private sector companies that I may not know about.
Public Sector	I live in a tropical country with an economy that still heavily dominated by commodities export the sustainability of biodiversity in the environment becomes very important.
Public Sector	The influence of transition related measures such as tariffs, offsets and financial market instruments leading to suboptimal conservation behavior.
Public Sector	Biodiversity risks may affect the economy and thereby price stability.
Public Sector	Biodiversity risks are a serious threaten to financial stability and the resilience of financial companies. As such, they have a strong impact on my professional life.
Public Sector	Potential regulatory developments.
Public Sector	Looking for ways to modernize economic thinking that humans are part of nature and human capital is a component of natural capital. Good, robust natural capital depends on biodiversity.
Public Sector	Absolutely. Loss of biodiversity and area for animals animals to move closer to cities, causing a great chance for diseases to spread to humans, which may cause another pandemic. There's dozens of other examples I could also list.
Academic Institution	Impacts the food and bevearge industry with whom I work closely.
Academic Institution	Yes, research on the link between human rights and climate - biodiversity protection.
Academic Institution	As a researcher, it is an imperative that scholars support corporates and other organizations in mitigation and adaptation to limit biodiversity loss risk.
Academic Institution	it is a main issue of assessing the value of natural capital.
Academic Institution	I think biodiversity risks are important for non-financial aspects of utility such as tourism and leisure. They may combine with other changes underway to create a worse planet. I am not sure if they would be paramount to financial economics, other than perhaps via impact on health, pharma, medicine, etc., where biodiversity serves a useful purpose as an essential input to innovative solutions to problems pertinent to common man (who is not much in finance!).

Note: Participants were asked: Are there any particular ways in which biodiversity risks are important in your professional life?

Table A.3: BERT classification examples: NYT

Panel A: Negative Sentences	
biodiversity	It is hard to believe that the Trump administration and the current Senate will be any more enthusiastic about preserving **biodiversity** than the Senate was then.
deforestation	Environmental problems remain, including overfishing and the erosion and **deforestation** left from earlier eras.
habitat	The antelope's numbers, once in the millions, have been severely depleted by illegal hunting, **habitat** loss and competition for food.
marine	There is concern, too, about the effect of broken-down plastic on **marine** life.
species	Even so, in August, the United States Fish and **Wildlife** Service withdrew its proposal to list the animal as a "threatened" species under the Endangered **Species** Act.
Panel B: Positive Sentences	
biodiversity	These organic seed sellers share a passion for the unusual and a mission to preserve **biodiversity**.
species	It highlights where endangered wild lands are being preserved, threatened **species** are being protected, historical wrongs are being acknowledged and fragile communities are being bolstered.
desertification	In the mid-2000s, African leaders envisioned creating a huge swath of greenthat could help combat **desertification** and land degradation.
habitat	In cities, trees cool hot streets, absorb pollution, improve air quality, limit storm water runoff, prevent erosion, enhance the physical and mental health of human beings, and provide desperately needed **habitat** for wildlife.

Note: Sentences classified as positive are assigned a score of 1, and sentences classified as negative are assigned a score of -1.

Table A.4: Example Sentences From 10-K

Panel A: Negative Sentences	
Materials	Long-term, higher average global temperatures could result in induced charges in natural resources, growing seasons, precipitation patterns, weather patterns, species distributions, water availability, sea levels, and **biodiversity**.
Energy	If our access to materials under **biodiversity** access agreements or other arrangements is reduced or terminates, it could harm our internal and our collaborative research and development efforts.
Consumer Services	These risks include the increased public focus, including by governmental and nongovernmental organizations, on these and other environmental sustainability matters, such as packaging and waste, animal health and welfare, **deforestation** and land use.
Pharma., Biotech., & Life Sc.	The natural oils and fats route can lead to concerns of **deforestation** due to the rapid expansion of palm oil plantations to meet growing demand.
Energy	If one of our LNG terminals or pipelines adversely affects a protected species or its **habitat**, we may be required to develop and follow a plan to avoid those impacts.
Panel B: Positive Sentences	
Semi. & Equip.	We leverage our expertise to develop new solutions to help restore natural resources, regenerate the quality of our **biosphere** and reduce carbon emissions.
Pharma., Biotech., & Life Sc.	We believe that growth of hemp could significantly reduce **deforestation** by providing the same products that trees are able to supply.
Materials	The Company follows Sustainable Forestry Initiative ('SFI') Standards that promote sustainable forest management in North America through the use of core principles, objectives, performance measures and indicators to protect water quality, **biodiversity**, wildlife habitat, species at risk, and forests which have exceptional conservation value.
Real Estate	Such forest practices include planting 300 to 600 seedlings on each acre, thinning **forest** stands to give remaining trees more room to grow, pruning selected trees to produce knot-free wood, fertilizing stands to supplement natural nutrient levels, and harvesting at sustainable rates-approximately 2 percent of our forestlands each year in the West and 3 percent in the South where the growing cycle is faster.
Materials	Our efforts to advance sustainable **forest** management and restore **forest** landscapes are an important lever for mitigating climate change through carbon storage in forests.

Note: Sentences classified as positive are assigned a score of 1, and sentences classified as negative are assigned a score of -1. Panel A shows the sentences that are classified as negative by BERT, while Panel B presents the positive sentences.

Table A.4: Example Sentences From 10-K (cont.)

Panel C: Neutral Sentences	
Food, Bev. & Tobacco	The Company continues to own the property and continues to conduct its long-term water dispersement program and **wildlife** management programs.
Energy	Fish and Wildlife Service (the 'FWS') announced a series of changes to the rules implementing the ESA, including revisions to the regulations governing interagency cooperation, listing species and delisting critical **habitat**, and prohibitions related to threatened wildlife and plants.
Materials	The U.S. EPA alleges the original **wetland** area has been partially filed by various waste handling and disposal activities which started as early as the 1940's.
Retailing	In fiscal 2018, we published an updated wood sourcing policy to ensure that all wood products sold in our stores originate from well-managed, non-endangered **forests** and committed to achieve 100 percent Forest Stewardship Council (FSC) certification for all wood products sourced from identified regions at risk by 2020.
Capital Goods	If endangered **species** or their **habitats** are identified, ESA requirements for protection, mitigation or avoidance apply.
Panel D: Transition Sentences	
Energy	A critical **habitat** or suitable habitat designation could result in further material **restrictions** to federal land use and may materially delay or prohibit access to protected areas for natural gas and oil development.
Consum. Durables & Apparel	Recent regulatory action involving the listing of a certain **species** of gopher as 'threatened' under the federal Endangered Species Act may adversely affect this project, for example by imposing new **restrictions** and requirements on our activities there and possibly delaying, halting or limiting, our development activities.
Materials	In addition, future domestic or foreign legislation or **regulation**, litigation advanced by Aboriginal groups and litigation concerning the use of timberlands, forest management practices, the protection of endangered **species**, the promotion of **forest biodiversity** and the response to and prevention of catastrophic wildfires could also affect timber supplies.
Real Estate	Federal, state and local **laws** and regulations, as well as those of other countries, which are intended to protect threatened and endangered **species**, as well as waterways and wetlands, limit and may prevent timber harvesting, road building and other activities on our timberlands.

Note: Panel C shows the neutral sentences identified by BERT. Panel D presents examples of sentences marked as biodiversity transition risk sentences.

Table A.5: Biodiversity Scores Rankings

GICS	Description	Avg.	(1)	(2)	(3)	(4)	(5)	(6)
1010	Energy	23.7	24	24	24	24	22	24
5510	Utilities	21.0	22	23	23	19	17	22
6010	Real Estate	17.8	20	20	20	18	19	10
1510	Materials	17.2	23	3	22	22	20	13
2520	Consum. Durables & Apparel	16.0	18	22	17	14	13	12
2010	Capital Goods	13.3	21	21	18	10	7	3
2030	Transportation	12.7	14	1	16	20	16	9
3520	Pharma., Biotech., & Life Sc.	12.5	16	7	1	21	23	7
2020	Commercial & Prof. Serv.	11.5	17	4	19	6	6	17
2550	Retailing	11.5	13	19	1	7	10	19
2530	Consumer Services	10.0	19	2	21	7	10	1
3020	Food, Bev. & Tobacco	9.8	1	6	1	23	24	4
4030	Insurance	9.7	1	7	1	17	18	14
2510	Auto & Components	9.5	1	7	1	14	13	21
4010	Banks	8.5	1	7	1	11	8	23
3510	Health Care Equip. & Serv.	8.0	1	7	1	13	21	5
3030	Household & Pers. Prod.	7.8	1	7	1	14	13	11
4020	Diversified Financials.	7.3	1	7	1	11	8	16
4520	Tech. Hardw. & Equip.	7.2	15	5	1	1	1	20
3010	Food & Staples Retailing	5.7	1	7	1	7	10	8
5020	Media & Entertainment	4.8	1	7	1	1	1	18
5010	Communication Services	4.3	1	7	1	1	1	15
4510	Software & Services	2.8	1	7	1	1	1	6
4530	Semiconductors & Equip.	2.2	1	7	1	1	1	2

Note: Industry biodiversity scores measured by (1) 10K-Biodiversity-Count, (2) 10K-Biodiversity-Negative, (3) 10K-Biodiversity-Regulation Score, (4) Survey-Transition Score, (5) Survey-Physical Score and (6) Holding-based score. The industries are sorted by the average score across the six measures and are based on data from 2019.

Table A.6: Correlation of Survey-based Average Industry Rankings Across Subgroups

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Role											
(1) Academic	1.00										
(2) Private Sector	0.97	1.00									
(3) Public Sector	0.98	0.95	1.00								
Location											
(4) Asia	0.97	0.98	0.98	1.00							
(5) Europe	0.98	0.93	0.99	0.97	1.00						
(6) North America	0.99	0.99	0.97	0.98	0.95	1.00					
(7) ROW	0.96	0.91	0.93	0.90	0.94	0.94	1.00				
Concern											
(8) Very High	0.99	0.95	0.98	0.98	0.97	0.99	0.94	1.00			
(9) High	0.98	0.98	0.97	0.97	0.96	0.99	0.94	0.97	1.00		
(10) Low	0.98	0.99	0.96	0.97	0.94	0.99	0.94	0.97	0.98	1.00	
(11) No Concern	0.89	0.82	0.87	0.86	0.91	0.85	0.83	0.89	0.82	0.84	1.00

Note: Correlation of survey-based industry scores. The average survey score is computed as the average value of the transition score and physical score.

Table A.7: Composition of Survey Respondents

		Role			Location				Biodiversity Concern			
	Pooled	Academic Institution	Private Sector	Public Sector	North America	Europe	Asia	ROW	Very High	High	Low	No Concern
Role (%)												
Academic Institution	48	100	0	0	46	53	52	43	43	56	53	52
Private Sector	34	0	100	0	42	15	35	26	39	23	36	35
Public Sector	18	0	0	100	13	31	13	31	18	20	11	13
Location (%)												
North America	62	59	76	43	100	0	0	0	58	60	71	70
Europe	23	26	10	41	0	100	0	0	23	27	15	13
Asia	9	10	10	7	0	0	100	0	11	9	11	13
Rest of the World	5	5	4	9	0	0	0	100	9	4	3	3
Ecosystem Diversity Loss Concern (%)												
Not at all important	8	9	9	5	9	6	9	6	1	3	9	100
Slightly important	24	26	23	20	26	20	26	14	6	27	91	0
Moderately important	35	37	28	40	34	36	38	26	19	69	0	0
Very important	34	28	40	35	31	38	28	54	73	0	0	0
Species Diversity Loss Concern (%)												
Not at all important	7	7	6	11	8	6	7	9	1	1	9	100
Slightly important	20	22	19	18	22	19	19	11	8	17	91	0
Moderately important	42	46	34	46	40	50	36	40	26	82	0	0
Very important	30	25	41	25	30	25	38	40	66	0	0	0
Graduation Year (%)												
Before 2000	30	29	35	24	33	27	13	35	30	32	20	32
Between 2000 and 2009	30	28	32	30	27	35	33	29	30	26	41	39
After 2010	40	44	33	46	40	38	53	35	40	41	39	29

Note: The percentage breakdowns in the table are to be read in columns within blocks. For example, the share of finance academics in North America is 46%, while the share of North American respondents among finance academics is 59%. The total number of respondents is 668. The table shows the distribution among respondents who answered the question of interest. The level of Biodiversity Concern shown in the column is determined by the maximum value between Ecosystem Diversity Loss Concern and Species Diversity Loss Concern.

Table A.8: Mapping GICS and NAICS Industries

NAICS		GICS	
Code	Name	Code	Name
11	Agriculture, Forestry	1510	Materials
11	Agriculture, Forestry	3020	Food, Beverage & Tobacco
21	Mining, Oil and Gas	1010	Energy
22	Utilities	5510	Utilities
23	Construction	1510	Materials
31-33	Manufacturing	2510	Automobiles & Components
42	Wholesale Trade	2010	Capital Goods
44-45	Retail Trade	2550	Retail
48-49	Transportation and Warehousing	2030	Transportation
51	Information	4520	Technology Hardware & Equipment
52	Finance and Insurance	4030	Insurance
52	Finance and Insurance	4020	Financial Services
53	Real Estate and Rental and Leasing	6010	Real Estate
54	Professional, Scientific, and Technical Services	2020	Commercial & Professional Services
55	Management of Companies and Enterprises	2020	Commercial & Professional Services
56	Administrative Services	2020	Commercial & Professional Services
61	Educational Services	2020	Commercial & Professional Services
62	Health Care and Social Assistance	3510	Health Care Equipment & Services
71	Arts, Entertainment, and Recreation	5020	Media & Entertainment
72	Accommodation and Food Services	3020	Food, Beverage & Tobacco
81	Other Services (except Public Administration)	2510	Automobiles & Components

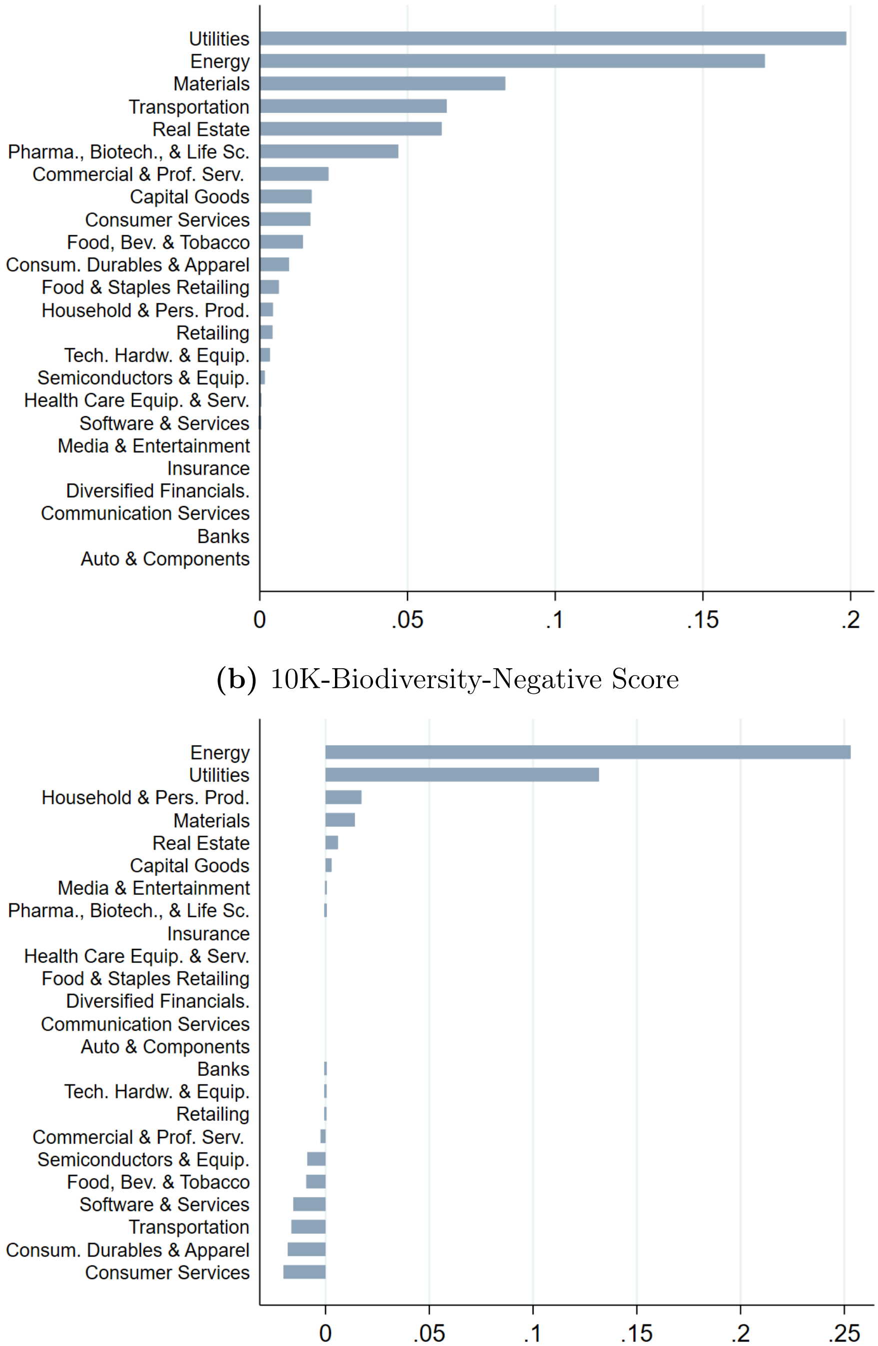
Note: NAICS industry detail is based on the 2012 North American Industry Classification System. GICS industry detail is based on the Global Industry Classification Standard in 2023. The crosswalk between categories is constructed manually. For NAICS industries that are matched with two GICS industries (Code 11 and Code 52), the GDP or employment is assigned equally to each GICS industry.

A.2 Figures

Figure A.1: Industry Rankings with Biodiversity Measures

(a) 10K-Biodiversity-Count Score

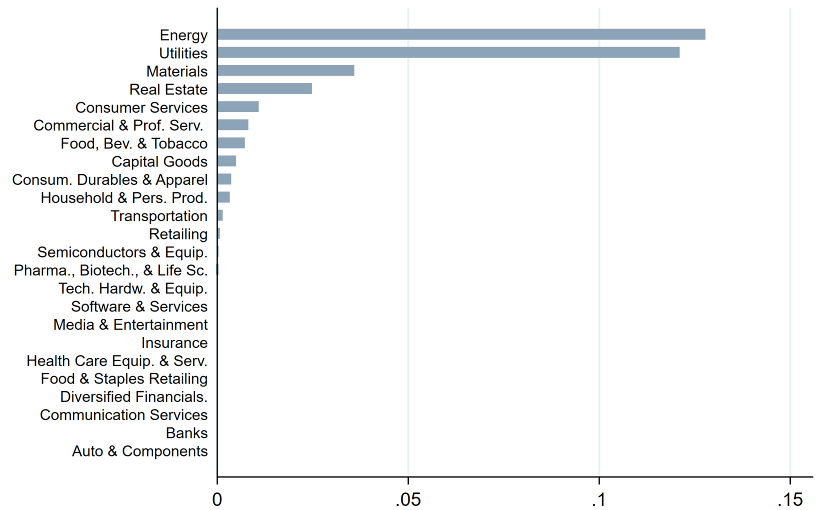
(b) 10K-Biodiversity-Negative Score



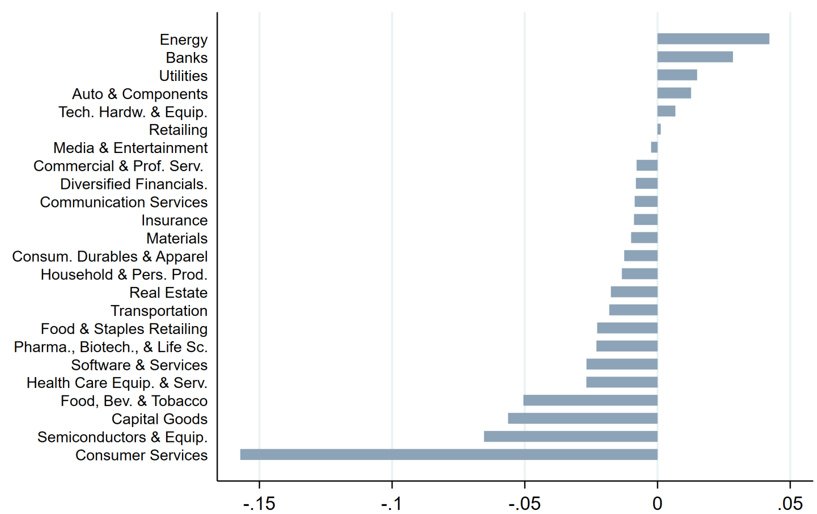
Note: Average industry-level 10K-based Biodiversity Scores using data from 2010 to 2020.

Figure A.1: Industry Rankings with Biodiversity Measures (cont.)

(c) 10K-Biodiversity-Regulation Score



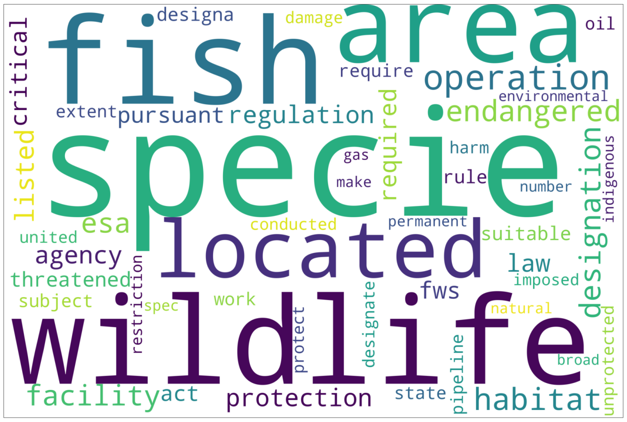
(d) Holding-based Score



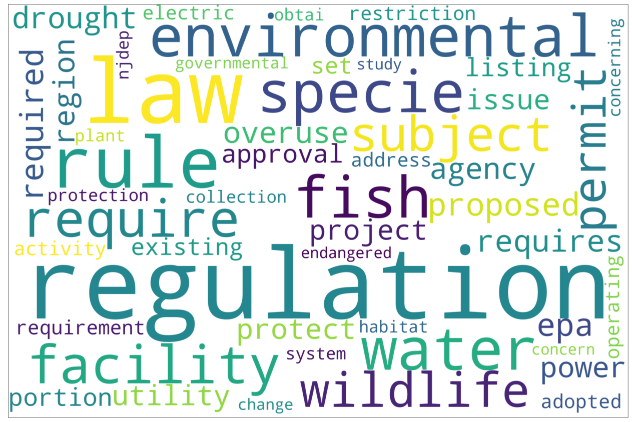
Note: Panel C shows the average industry-level 10K-Biodiversity-Regulation Scores using data from 2010 to 2020 and Panel D shows the Holding-based Score using data in December 2022.

Figure A.2: Word Cloud: Biodiversity Vocabulary by Sector

(a) Energy Sector

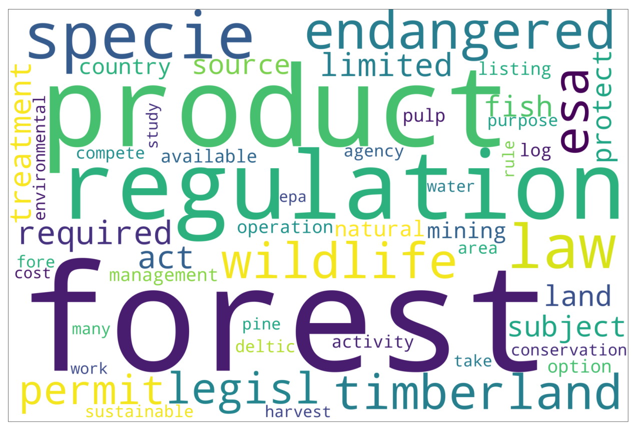


(b) Utilities Sector



(c) Real Estate Sector

(d) Materials Sector



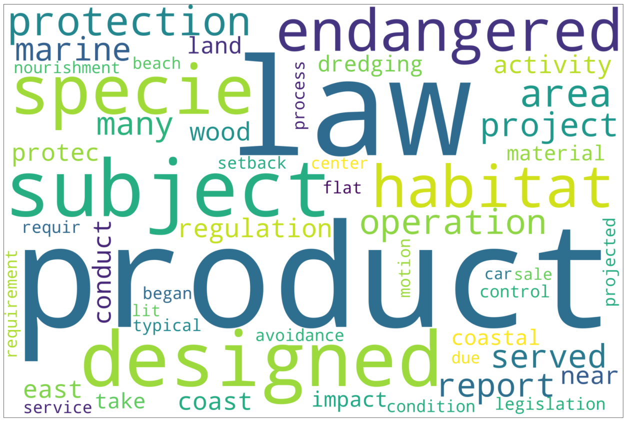
(e) Consumer Services

(f) Consumer Durables & Apparel Sector

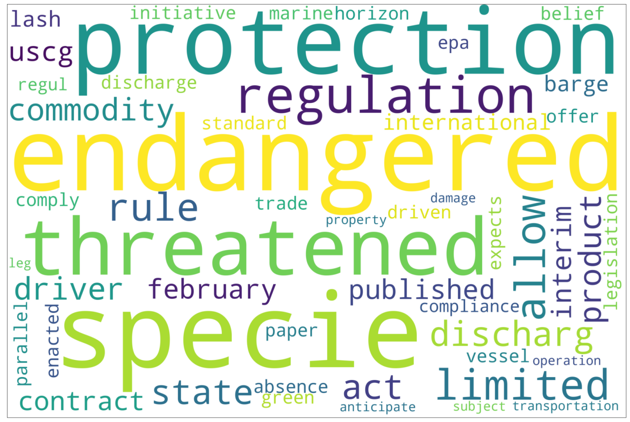
Note: Word cloud summary of vocabulary from biodiversity sentences mention in firms' 10K statement. Term sizes are proportional to their frequency in the corpus.

Figure A.2: Word Cloud: Biodiversity Vocabulary by Sector (cont.)

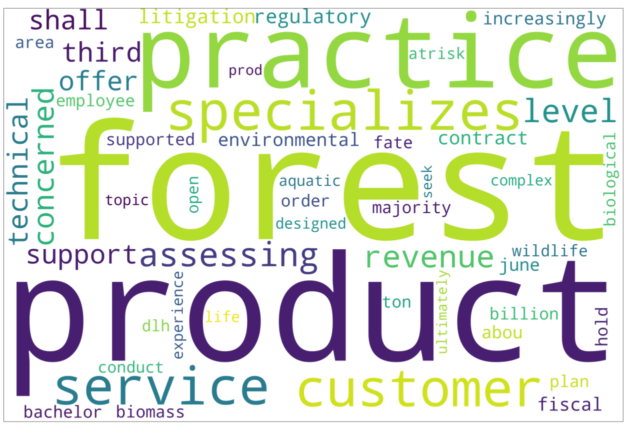
(g) Capital Goods Sector



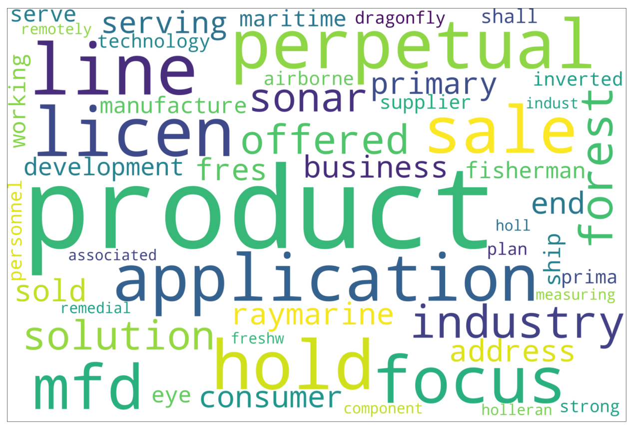
(h) Transportation Sector



(i) Commercial & Professional Services Sector

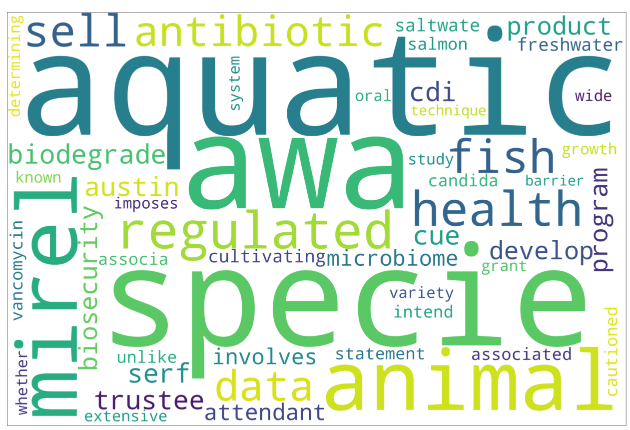


(j) Technology Hardware & Equipment Sector



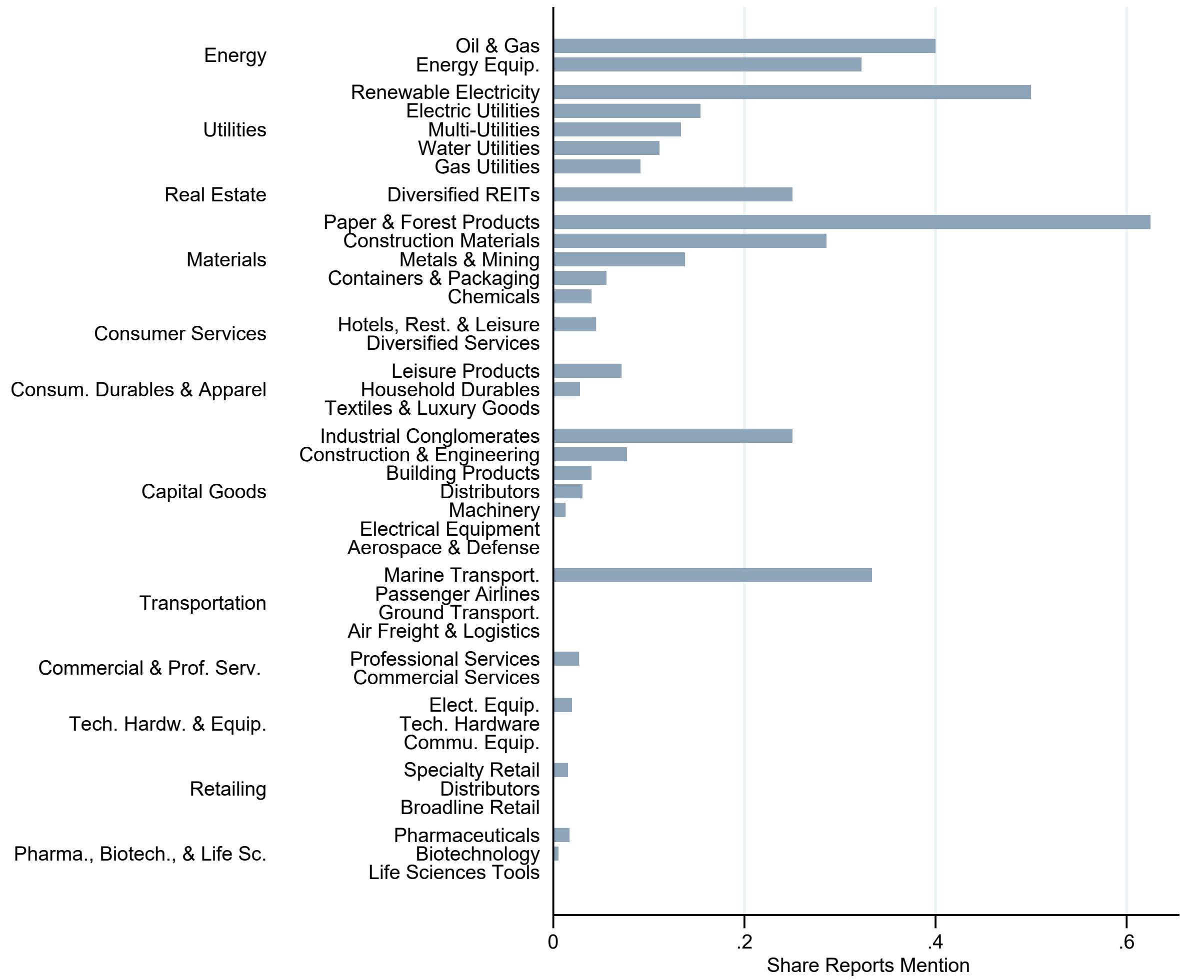
(k) Retailing Sector

(l) Pharma., Biotech. & Life Sciences Sector



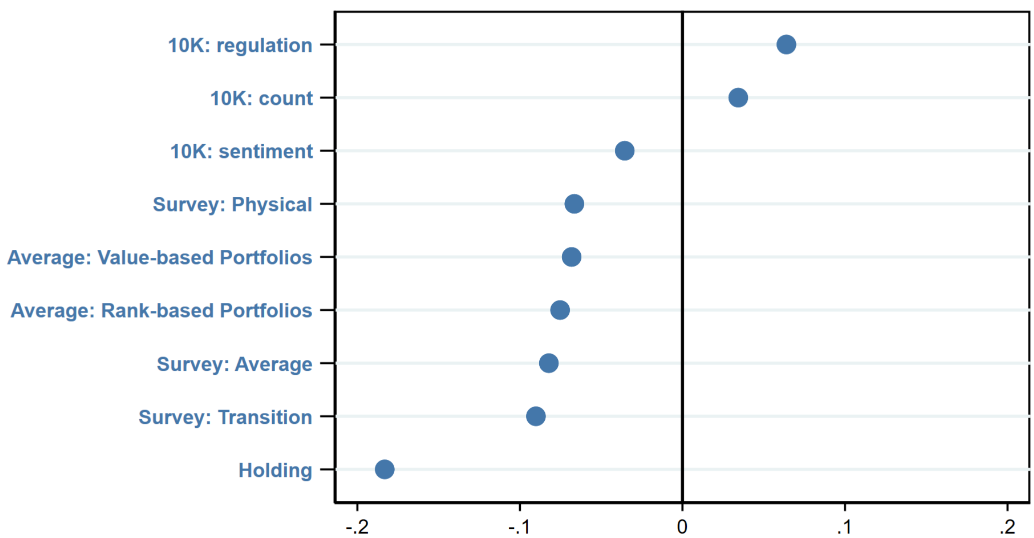
Note: Word cloud summary of vocabulary from biodiversity sentences mention in firms' 10K statement. Term sizes are proportional to their frequency in the corpus.

Figure A.3: Industry and Subindustry Rankings with Biodiversity Measures



Note: The figure displays the ranking of industry biodiversity risk exposure, sorted by both 4-digit and 6-digit GICS industry codes. This exposure is measured by the proportion of 10-K statements that mention biodiversity in the corresponding 6-digit sector. We keep the 4-digit industries only when at least one of the 6 digits has a mention and drop the rest, including Automobiles & Components, Consumer Staples Distribution & Retail, Food, Beverage & Tobacco, Personal Care Products, Health Care Equipment & Services, Banks, Financial Services, Insurance, Software & Services, Semiconductors & Semiconductor Equipment, Telecommunication Services, and Media & Entertainment.

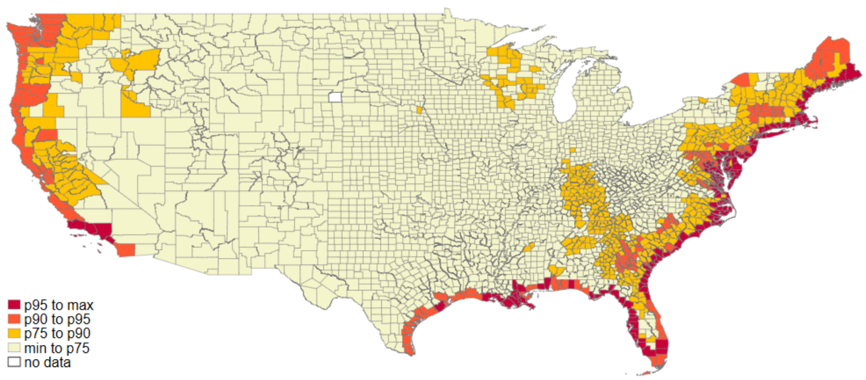
Figure A.4: Biodiversity Hedge Performance of Various Portfolios Before 2010



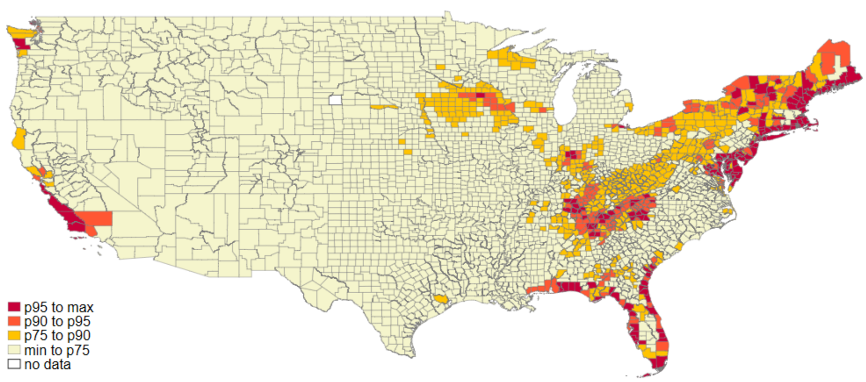
Note: Dot plot of monthly return correlations for various biodiversity hedge portfolios with AR(1) innovations of NYT-Biodiversity Risk Index using data from 2000 to 2009. Each dot represents one correlation coefficient.

Figure A.5: Spatial Distribution of Endangered Species Score

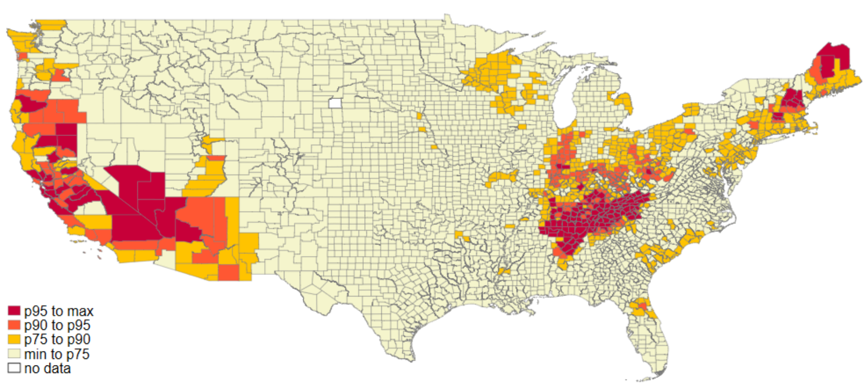
(a) Marine Species



(b) Terrestrial Species



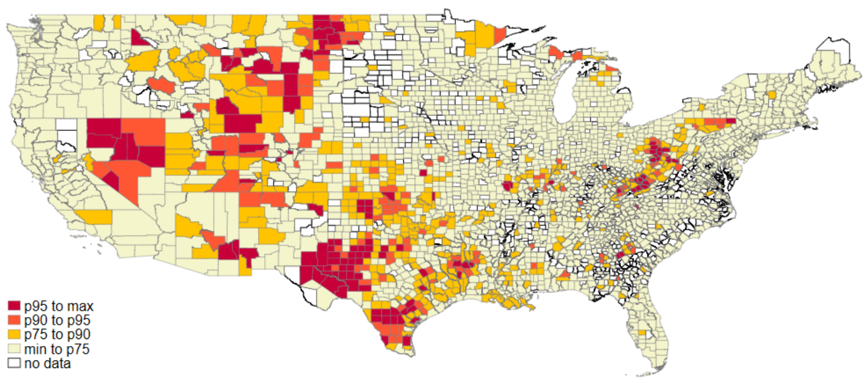
(c) Freshwater Species



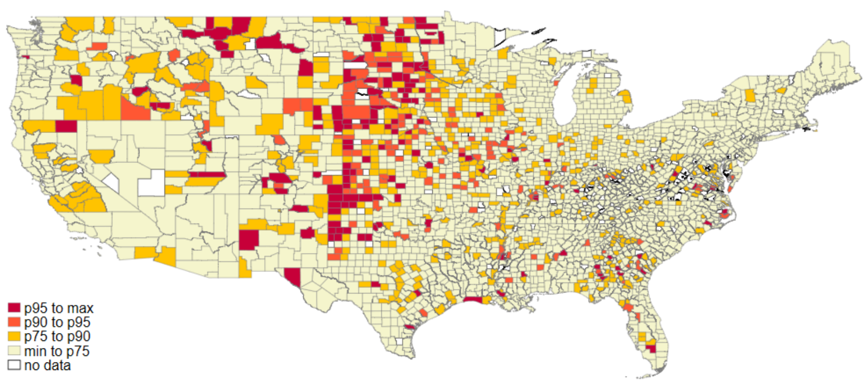
Note: Distribution of the "Endangered Species Score". The score is computed as the share of marine / terrestrial / freshwater endangered species (% total marine / terrestrial / freshwater species). Data source: IUCN Red List of Threatened Species, 2022 version.

Figure A.6: Spatial Distribution of GDP Shares

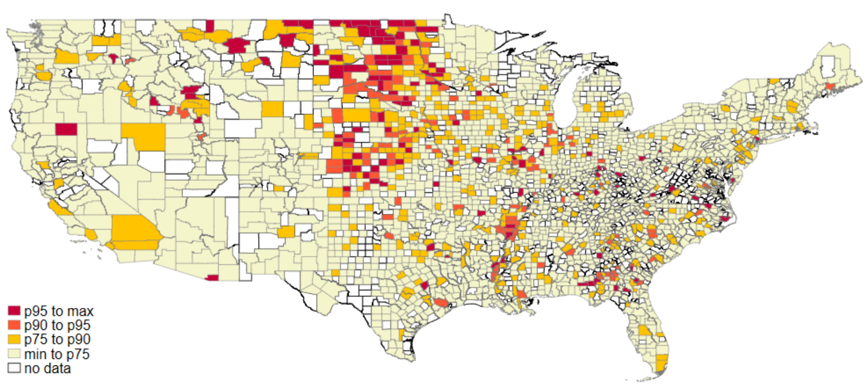
(a) Energy



(b) Materials



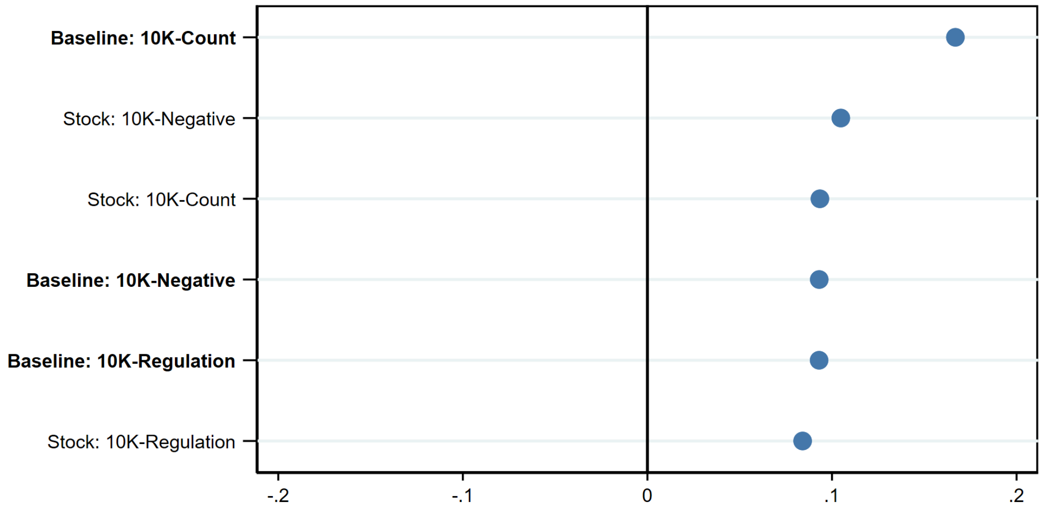
(c) Capital Goods



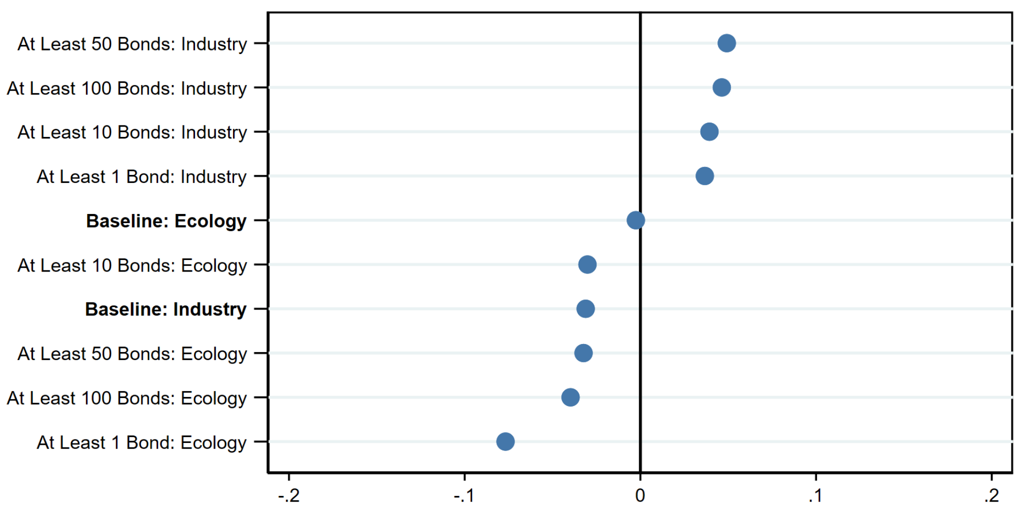
Note: Distribution of Energy, Materials and Capital Goods sectors in 2020. Counties with darker colors have higher GDP shares in Energy / Materials / Capital Goods sectors. Data source: Bureau of Economic Analysis.

Figure A.7: Biodiversity Hedge Performance - Robustness Tests

(a) Equities



(b) Municipal Bonds



Note: Dot plot of monthly return correlations for various portfolios with AR(1) innovations of NYT-Biodiversity Risk Index using data from 2010 to 2020. Panel A shows the characteristic-sorted portfolios at the industry level (in bold) and at the individual stock level. Panel B shows the characteristic-sorted portfolios of municipal bonds constructed with returns of all counties (in bold) and of counties with higher trading frequencies, described in the text.

A.3 Screenshots of Survey Flow

Figure A.3.1: Survey Introduction

We invite you to participate in a survey exploring your views on the importance of various biodiversity risks for investors and firms. This study aims to learn more about perceptions of biodiversity risk among academics and professionals. The survey is being conducted by Professor Stefano Giglio of Yale SOM, Professor Johannes Stroebel, Professor Theresa Kuchler and Xuran Zeng of NYU Stern.

If you agree to participate in this study, you will be asked to fill out a brief survey. Participation in this study will take about 5 minutes. There are no known risks associated with your participation in this research.

Since we are not collecting any personally identifiable information, the confidentiality of your responses will be maintained. Participation in this study is voluntary. You may refuse to participate or withdraw at any time without penalty. You have the right not to answer any questions you prefer not to answer.

If there is anything about the study or your participation that is unclear or that you do not understand, or if you have questions or wish to report a research-related problem, you may contact Xuran Zeng at xz4183@stern.nyu.edu.

For questions about your rights as a research participant, you may contact the Committee on Activities involving Human Subjects (UCAIHS), New York University, 665 Broadway, Suite 804, New York, New York 10012, at ask.humansubjects@nyu.edu or (212)998-4808. Please reference the study #(IRB-FY2023-7423) when contacting the IRB (UCAIHS).

Thank you very much for your participation.

Stefano Giglio, Theresa Kuchler, Johannes Stroebel and Xuran Zeng
Yale SOM & NYU Stern

○ I consent to participate in this study

Figure A.3.2: General Information

How is the institution at which you work best described?

- ○ Academic Institution
- ○ Public Sector
- ○ Private Sector

Where are you located?

- ○ North America
- ○ Europe
- ○ Asia
- ○ Rest of the World

What is your graduation year?

- ○ Before 2000
- ○ Between 2000 and 2009
- ○ After 2010

→

Figure A.3.3: Importance of Biodiversity Risk

How worried are you about the following aspects of biodiversity loss?

	Not at all worried	Not very worried	Somewhat worried	Very worried
Ecosystems Diversity Loss	○	○	○	○
Species Diversity Loss	○	○	○	○

Biodiversity risks for investors and firms are often divided into (i) physical risks coming from actual changes in biodiversity (e.g., reduced pollinators, freshwater scarcity) and (ii) transition risks coming from changes in the regulatory environment to combat biodiversity loss (e.g., the Clean Water Act). Please rate the financial materiality of these risks for corporations in the United States.

	Not at all important	Slightly important	Moderately important	Very important
Physical Biodiversity Risks	○	○	○	○
Transition Biodiversity Risks	○	○	○	○

Over what time horizon, if any, do you expect these biodiversity risks to materialize?

	Already today	1 to 5 years	5 to 30 years	More than 30 years	Never
Physical Biodiversity Risks	○	○	○	○	○
Transition Biodiversity Risks	○	○	○	○	○

→

Figure A.3.4: Importance of Biodiversity Risk (Industry Exposure)

Select the industries that you believe are most negatively affected by physical risks from biodiversity loss.

- ☐ Energy
- ☐ Pharmaceuticals, Biotech & Life Sciences
- ☐ Materials
- ☐ Banks and Diversified Financials
- ☐ Capital Goods
- ☐ Insurance
- ☐ Commercial & Professional Services
- ☐ IT and Communication Services
- ☐ Transportation
- ☐ Consumer Services and Retailing
- ☐ Automobiles, Consumer Durables and Household Products
- ☐ Utilities
- ☐ Food, Beverage & Tobacco
- ☐ Real Estate
- ☐ Health Care

Select the industries that you believe are most negatively affected by biodiversity transition risks.

- ☐ Energy
- ☐ Pharmaceuticals, Biotech & Life Sciences
- ☐ Materials
- ☐ Banks and Diversified Financials
- ☐ Capital Goods
- ☐ Insurance
- ☐ Commercial & Professional Services
- ☐ IT and Communication Services
- ☐ Transportation
- ☐ Consumer Services and Retailing
- ☐ Automobiles, Consumer Durables and Household Products
- ☐ Utilities
- ☐ Food, Beverage & Tobacco
- ☐ Real Estate
- ☐ Health Care

→

Figure A.3.5: Pricing of Biodiversity Risks

To what extent do you think that physical or transition biodiversity risks are currently priced int he following asset markets?

	Not enough	Correct	Too much	No opinion
Stock Markets	○	○	○	○
Commodity Markets	○	○	○	○
Sovereign Debt Markets	○	○	○	○
Real Estate Markets	○	○	○	○

Are there any particular ways in which biodiversity risks are important in your professional life?

→

A.4 Additional Data Details

A.4.1 Surveyed Public Sectors

We gathered email addresses from a range of institutions that make researcher emails accessible on their institutional websites. The institutions are Banco Central de Chile, Banco Central de Reserva del Perú, Banco Central do Brasil, Banco de España, Banco de la república Colombia, Banco de México, Bangko Sentral ng Pilipinas, Bank for International Settlements, Bank Negara Malaysia, Bank of Canada, Bank of England, Bank of Finland, Bank of Israel, Bank of Japan, Bank of Korea, Banque de France, Central Bank of Malta, Central Bank of Thailand, Danmarks Nationalbank, De Nederlandsche Bank, Deutsche Bundesbank, European Central Bank, Federal Reserve Banks of Boston, Federal Reserve Banks of Chicago, Federal Reserve Banks of Dallas, Federal Reserve Banks of Minneapolis, Federal Reserve Banks of New York, Federal Reserve Banks of Philadelphia, Federal Reserve Banks of Richmond, Hongkong Monetary Authority, International Monetary Fund, National Bank of Georgia, Norges Bank, Reserve Bank of Australia, Reserve Bank of India, Reserve Bank of South Africa, United Nations, World Bank, World Economic Forum.

A.4.2 Biodiversity Sentences

We define the Biodiversity Dictionary that contains the following biodiversity-related terms: biodiversity, ecosystem(s), ecology (ecological), habitat(s), species, (rain)forest(s), deforestation, fauna, flora, marine, tropical, freshwater, wetland, wildlife, coral, aquatic, desertification, carbon sink(s), ecosphere, and biosphere. While certain unigrams, such as deforestation, effectively identify biodiversity sentences, others are not as precise due to their broad connotations. For example, the word "ecosystem" sometimes captures "software ecosystem,"[22] "marine" extracts "marine cargo insurance,"[23] "tropical" sometimes selects "tropical fruit."[24]

To avoid selecting sentences that are irrelevant to biodiversity, we employ other terms to narrow down the sentences for these particular words. A sentence will be classified as being related to biodiversity only if it contains both the specific biodiversity vocabulary and one of the following terms simultaneously. For example, a sentence will be selected if it contains both 'ecosystem" and "climate": "We understand the adverse effects of human behavior and **climate** change on **ecosystems** and the animals who call them home; therefore, we are constantly working to minimize the footprint of our operations."

- **Ecosystem(s):** climate, coast, forest, micro, natur, public health, sustaina, water
- **Marine:** marine biodiversity, marine ecosystem, marine environment, marine life, marine species

[22] "Our products primarily compete based on performance, energy efficiency, integration, ease-of-use, innovative design, features, price, quality, reliability, security features, **software ecosystem** and developer support, 'time-to-market, brand recognition, customer support and customization, and availability."

[23] "The Company maintains **marine cargo insurance** covering claims for losses attributable to missing or damaged shipments for which it is legally liable.

[24] "All of our **tropical fruit** shipments into the North American and core European markets are delivered using pallets or containers."

- **Tropical:** tropical biodiversity, tropical ecosystem, tropical environment, tropical forest, tropical species

- **Species:** aquatic, biodiversity, bird, endanger, environment, fish, habitat, invasive, list, marine, protect, threat, ESA, EPA

A.4.3 p-value Adjustment for Multiple Testing

In this section, we apply the Benjamini-Hochberg method (Benjamini and Hochberg (1995), BH) to study the statistical significance of the correlation between hedging portfolios sorted on the 207 stock characteristics and biodiversity risk innovations. The key idea of BH is to adjust the statistical significance threshold in a way that guarantees a "false discovery rate" control. That is, having chosen a threshold τ, the adjustment guarantees that in expectation, at most a fraction τ of the tests that are deemed significant by the test are in fact false positives (for more details, see Giglio et al. (2021c)). To apply the BH procedure, we proceed as follows.

First, we compute the (univariate) correlation between each of the 207 characteristics-sorted portfolios and the innovation of the NYT Biodiversity Risk Index over the period of 2010 to 2020 and get the standard p-values for the statistical test that these correlations are not zero. Then we sort all the p-values in ascending order, denoted as $p_{(1)} \leq ... \leq p_{(N)}$. The BH procedure recommends rejecting the null hypothesis that the correlation is zero, for each $i = 1, ..., N$, if $p_i \leq p_{(\hat{k})}$, where $\hat{k}$= max $\{i \leq N : p_{(i)} \leq \tau i/n\}$. In this test, N is 207 and we set τ to be 0.05 (the false discovery rate). We find that *none* of the 207 characteristics has a correlation lower than the cutoff, suggesting that the good hedging performance observed for some measures is the product of random chance.

To visualize these results, we invert the BH formula to compute adjusted p-values, that can each be compared with 0.05 to establish significance. For the sorted p-values, we compute the adjusted p-values as $\tilde{p}_i = p_i * N/i$, where i is the position in the ordering. Appendix Figure A.4.1 illustrates the distribution of these adjusted p-values. None of these adjusted p-values is below 0.05 (the minimum value is 0.14).

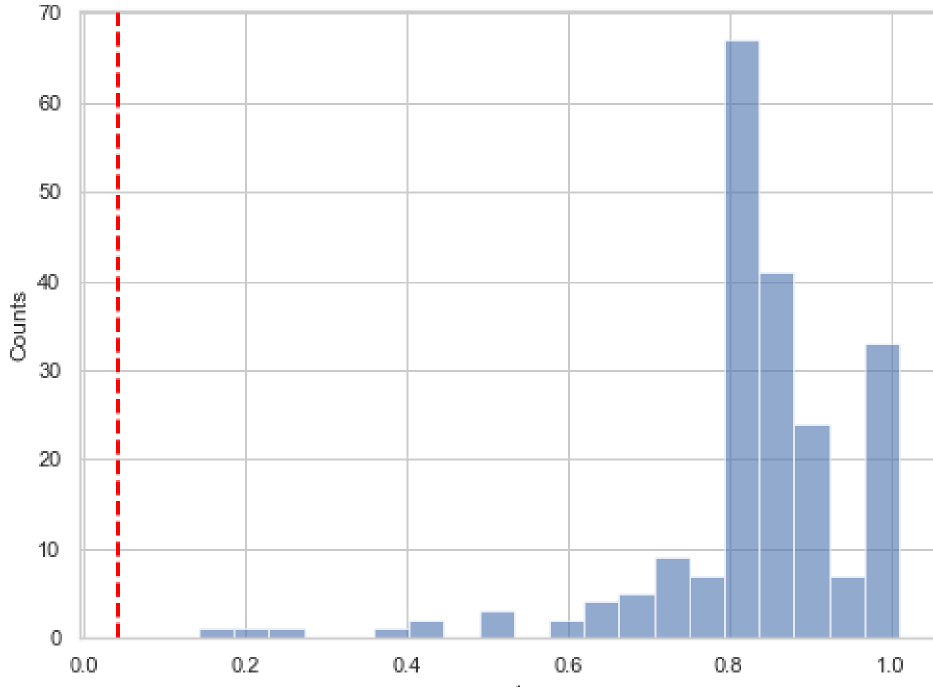
Finally, the figure also plots the (non-adjusted) p-value (0.0426) of the portfolio built using our average biodiversity risk measure. We do not adjust this p-value since our measures are economically motivated a priori.

This test suggests that none of these common factors in the factor zoo captures biodiversity risks and has a significantly non-zero correlation with innovations in the biodiversity risk index. In contrast, our economically motivated biodiversity measure shows significant hedging performance.

A.4.4 Global-level Biodiversity Risk Exposures

A number of research centers have published climate (or environmental) risk scores and ratings for countries, with biodiversity risk serving as a component (see, for example, Yale Environmental Performance Index and Notre Dame Global Adaptation Initiative). While these indices encompass a comprehensive set of ecological indicators, these assessments often

Figure A.4.1: Adjusted P-values Distribution



Note: The blue bars illustrate the adjusted p-values of the 207 characteristics using data from 2010 to 2020. The red dashed line represents the standard p-value of the portfolio constructed based on the average of our six biodiversity measures.

overlook the financial and economic dimensions of biodiversity risk. In this section, we therefore propose two new ways to measure countries' biodiversity exposures, using both economic data sources and ecological data : (i) IMF reports, and (ii) endangered species.

IMF-Biodiversity Score. Our first country-level measure of biodiversity risk exposures is based on countries' IMF Article IV reports[25]. The methodology is the same as 10-K based approach in section 2. We identify biodiversity-related sentences in IMF reports using regular expression searches for the same biodiversity dictionary. From 2010 to 2022, we have 670 sentences related to biodiversity. Then we manually classify the sentences into degradation or regulation. The following are two examples of biodiversity degradation sentences from IMF reports:

> The main impact of climate change will be through rising sea levels, but also warmer average temperatures and more frequent and severe storms. This would lead to permanent erosion of the shoreline and loss of land, frequent inundation,

[25]The IMF Article IV report is an annual assessment of the economic and financial policies of member countries. The report covers a wide range of economic and financial issues, including macroeconomic stability, fiscal policy, monetary policy, financial sector stability, and risk assessment. We collected 1492 reports from 2010 to 2022 from the IMF website, covering 194 countries and regions.

> lower biodiversity, lower agricultural production, and water resource and food security issues. [Kiribati 2015]
>
> Rapid urbanization and depletion of forest and water resources in recent years led to increased vulnerability to flood risks, land degradation, and biodiversity loss. [Rwanda 2021]

The following are two examples of biodiversity regulation sentences from reports:

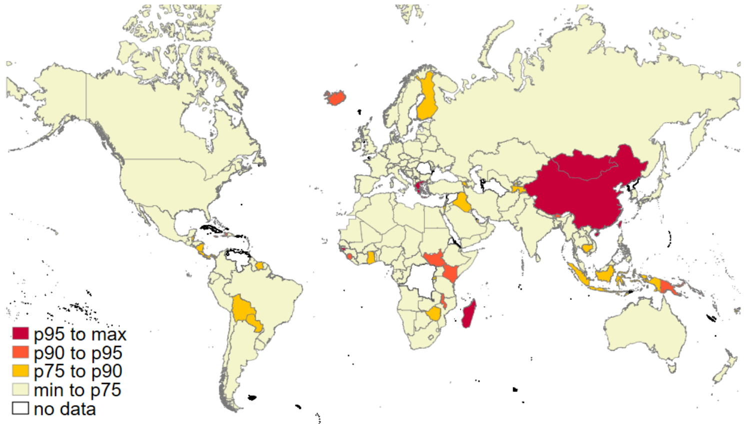
> The Seychelles Marine Spatial Plan (SMSP) Initiative began in 2014 to address climate change adaptation, marine biodiversity protection, and support for the Blue Economy. [Seychelles 2022]
>
> A GEF (Global Environment Facility) -funded Additional Financing operation is also anticipated in FY 18, to consolidate forest and biodiversity conservation efforts in the Amazon.[Colombia 2017]

If a report contains at least one biodiversity degradation / regulation sentence, we assign a score of '1' to the country. Panel A and B of Figure A.4.2 illustrate the global distribution of the average IMF-based biodiversity risk measures from 2010 to 2022, where a darker color indicates more mentions in the country. In line with the survey results, countries located in Asia and the rest of the world are more concerned about biodiversity compared to countries located in North America or Europe.

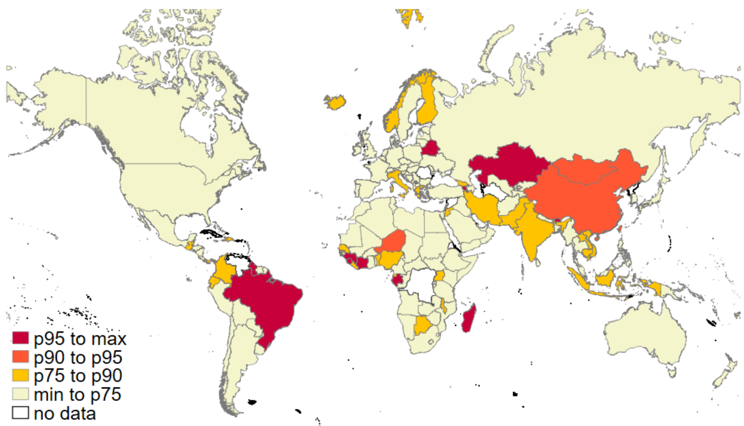
Endangered Species Score. The next set of ecological measures is based on the IUCN Red List of Threatened Species (2022 version). We compute the Endangered Species Score as the number of all endangered species divided by the number of all species for each country. Panel C of Figure A.4.2 displays the global distribution of Endangered Species Score for all species.

Figure A.4.2: Spatial Distribution of Country-level Biodiversity Scores

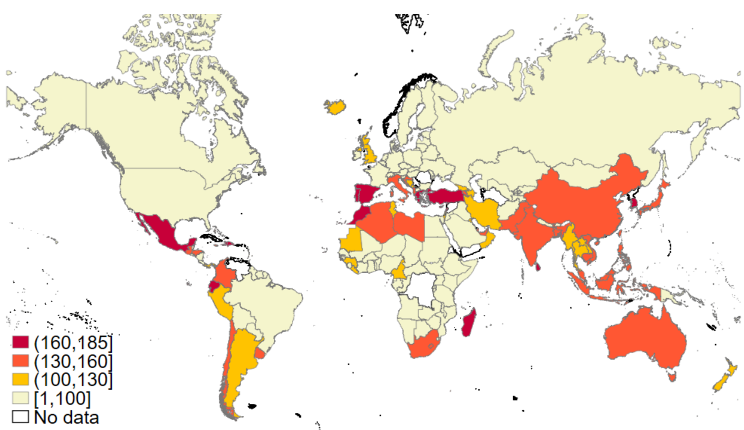
(a) IMF-Degradation Biodiversity Score



(b) IMF-Regulation Biodiversity Score



(c) Endangered Species Score Score



Note: Spatial Distribution of the country-level biodiversity risk measures. IMF-based scores use the average of scores from 2010 to 2022. Endangered Species Score uses data in 2022.

A.4.5 Municipal Bond Returns

In this section, we apply the methodology of Auh et al. (2022) to estimate monthly county-level municipal bond returns from infrequent trading data. The key idea is to compute the average of all municipal bond returns within the same county weighted by issue amount and trading interval.

Data. We construct bond returns using the Municipal Securities Rulemaking Board's (MSRB's) municipal bond transaction database, which includes information such as the CUSIP, trade date, the dollar price of the transaction, and type of transaction. To ensure a minimum level of trading liquidity, we exclude bonds with fewer than 10 trade observations. We also remove data errors by excluding observations with time to maturity of more than 100 years, coupon rate more than 20%, or a price lower than \$50 or greater than \$150 (on a \$100 notional). For each day, we calculate volume-weighted price averages for all intra-day trades and use the last available price of the month to obtain monthly prices. We obtain additional bond information from the Mergent Municipal Bond Database, including issue amount, CUSIP, and issue ID. To locate each municipal bond, we merge the MSRB and Mergent databases by CUSIP and then merge the resulting bond data with county-level biodiversity risk measures by issue ID, using the crosswalk from Acharya et al. (2022). Our final sample includes 150,666 bonds issued by 1,386 counties, with price data covering January 2005 through June 2022.

Return Estimation. Our estimation of the monthly return series is based on Auh et al. (2022) and follows insights from repeat-sales models in the housing market. It is based on the following model:

$$R_{i,b:s} = \sum_{t=b+1}^{s} R_t^c + e_{i,b:s}$$

where $R_{i,b:s} = log(p_{i,s}/p_{i,b})$, $R_t^c = log(1 + r_t^c)$. $p_{i,s}$ and $p_{i,b}$ are prices of bond i in months s and b ($s > b$) respectively. r_t^c denotes the monthly return in county c and month t. $e_{i,b:s} = \sum_{t=b+1}^{s} log(\epsilon_{i,t})$ where $\epsilon_{i,t}$ represents the bond-specific idiosyncratic return component. The monthly return R_t^c is estimated in panel regressions as the coefficient on the monthly indicator variables. Each of the $b - s$ monthly indicator variables is equal to one in the one month that falls between $b + 1$ and s and is equal to zero in all other months. We use weighted least squares regressions with the weight being the square root of issue amounts divided by the square root of the time interval between b and s.