**Horn, Matthias; Dabbous, Amal; Oehler, Andreas**

# Green finance, environmental policy and technological innovation as tools for managing nature-related risk and biodiversity loss

Date of secondary publication: 05.05.2026

Version of Record (Published Version), Article

Persistent identifier: urn:nbn:de:bvb:473-irb-114952x

**Primary publication**

Horn, Matthias; Dabbous, Amal; Oehler, Andreas (2026): Green finance, environmental policy and technological innovation as tools for managing nature-related risk and biodiversity loss, in: Journal of environmental economics and management : JEEM, Amsterdam [u.a.]: Elsevier, Vol. 404, No. 129317, pp. 1–14, doi: 10.1016/j.jenvman.2026.129317.

Journal of Environmental Management 404 (2026) 129317

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

# Green finance, environmental policy and technological innovation as tools for managing nature-related risk and biodiversity loss

Matthias Horn [a,*], Amal Dabbous [b], Andreas Oehler [c]

[a] Bamberg University, Bamberg, Germany
[b] Saint-Joseph University of Beirut, Lebanon
[c] Chair of Finance, Bamberg University, Bamberg, Germany

ARTICLE INFO

*JEL classification:*
Q01
Q50
Q57
Q5

*Keywords:*
Nature risk
Green bond
Technological innovation
Environmental policy stringency
Biodiversity
Biocapacity
Ecological footprint

ABSTRACT

The twin crises of biodiversity loss and climate change are putting the world's ecosystem services under pressure and intensifying nature-related risks. This poses significant threats to human well-being and economic development, as nations' economic activities depend on ecosystem services. This study adopts a novel approach and assesses countries' nature risk based on the LEAP framework. This implies mapping the ecological resources of a country and evaluating how much the country depends on these resources. Therefore, the study applies a country's ecological budget and ecosystem dependency to assess the nature risk position of 45 countries over the period 2014–2021. Since nations show different profiles in both their ecological capacity and their dependency on ecosystem services, it is assumed that nature risk mitigating measures do not have a uniform effect among all countries. We analyze this issue by grouping countries into different risk groups. The results show a positive relationship between nature risk and risks to future economic growth, measured as GDP risk. The findings also reveal that higher green bond issuance, more stringent environmental policies, and greater technological advancement are associated with nature risk mitigation by increasing biodiversity and ecological budget while reducing the ecological footprint. More specifically, these three mitigating factors seem to operate mainly through two channels: increased use of renewable energy and decreased energy intensity. Overall, the results indicate that active nature risk management can reduce countries' vulnerability to climate change and biodiversity loss and provide concrete guidance for policymakers designing nature risk mitigation strategies.

## 1. Introduction

The global economy relies on ecosystem services, i.e., the variety of benefits that nature provides. The value of the global ecosystem services is estimated to be equivalent to 1.5 times the global GDP (OECD, 2019). A study published in 2020 by the World Economic Forum “shows that $44 trillion of economic value generation – more than half of the world's total GDP – is moderately or highly dependent on nature and its services and is therefore exposed to nature loss.” (World Economic Forum, 2020, p.8).

Ecosystem services are under pressure from two major threats: the climate crisis and the loss of biodiversity. Particularly, when the global mean temperature rises greater than 2 °C above preindustrial levels, there will be a significant net negative effect on many ecosystem services (Scholes, 2016). Ignoring the importance of ecosystems can lead to major environmental issues such as the depletion of natural resources, global warming, and climate change (Khezri et al., 2021). Biodiversity is not only a regulator of ecosystem processes, determining the resilience to pests and environmental change, but it is also an ecosystem service by itself, e.g., because genetic and wild species diversity contributes to new medicines and crops (Mace et al., 2012; Shaw et al., 2025). A loss in biodiversity, therefore, has a significant negative effect on ecosystem services (Costanza et al., 2007). Biodiversity loss is a serious issue to consider, particularly since the economic costs driven by this problem are at least as high as those generated by climate change (Hudson, 2024).

However, the relationship between economic development, ecosystem services, the climate crisis, and biodiversity has several more facets. With increasing temperatures, biodiversity loss becomes faster and more severe, with extinction rates that would qualify as the sixth mass extinction in the history of the earth (Bellard et al., 2012). Moreover, higher and more volatile temperatures increase firms'

* Corresponding author. Department of Finance, Bamberg University, Kaerntenstr. 7, 96045, Bamberg, Germany.
*E-mail addresses:* matthias.horn@uni-bamberg.de (M. Horn), amal.dabbous@usj.edu.lb (A. Dabbous), andreas.oehler@uni-bamberg.de (A. Oehler).

https://doi.org/10.1016/j.jenvman.2026.129317
Received 15 December 2025; Received in revised form 2 March 2026; Accepted 9 March 2026
Available online 12 March 2026

environmental risk and reduce economic performance (Bettarelli et al., 2025). More frequent and more severe natural disasters cause direct economic damage (Nordhaus, 2019). Further, biodiversity loss exerts a direct influence on economic development since it limits resource availability and leads to higher costs across industries, making resource procurement more expensive (Becker et al., 2025). Nations' economic activities highly rely on the main ecosystem services like soil and water on the one hand. On the other hand, the economic actions can damage the ecosystem through resource depletion (Becker et al., 2025). Hence, while ecosystem services are vital for economic development, higher economic development has led to larger biodiversity loss (Habibullah et al., 2022) and more greenhouse gas emissions (Ansuategi and Escape, 2002).

Nevertheless, it is clear that the climate crisis and the loss of biodiversity are major risks for the economy. Biodiversity loss has been increasing in recent decades mainly due to climate change and human-driven activities (Santos et al., 2020; Wang et al., 2024). For instance, climate change problems like irregular variations in precipitation and temperatures can raise forest fires, which pose an essential biodiversity threat (Brodie et al., 2012). Temperature increases raise the gravity and frequency of natural disasters like droughts, floods, and extreme temperature changes (Song et al., 2023). Within this study, we refer to nature related risk as the risk driven by both the climate crisis and the degradation of ecosystem services and biodiversity. Biodiversity is defined as "the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are a part. This includes variation in genetic, phenotypic, phylogenetic, and functional attributes, as well as changes in abundance and distribution over time and space within and among species, biological communities, and ecosystems." (Díaz et al., 2015; IPBES, 2024; NGFS, 2023). Biodiversity loss refers to the decrease in species' varieties and ecosystem fragility (Becker et al., 2025). According to Nilsson and Grelsson (1995), fragile ecosystems are the ones characterized by fast variations in the number of species, while stable ecosystems are characterized by lower levels of fluctuations and larger resilience.

However, it has to be considered that not all areas of the world will be affected similarly by these risks. Most living species inhabit three main rainforest systems (Amazon, Congo, and Indonesian) (Swanson and Groom, 2012). Further, an inverse correlation is believed to exist between forms of wealth and species richness, some nations are considered among the wealthiest in biodiversity but the poorest in income (Swanson and Groom, 2012). Therefore, it is essential to consider country-specific risks when assessing necessary biodiversity conservation measures or climate change mitigation strategies. Some countries may be better prepared to handle the risks than others because of their ecological budget and development status.

Only a few organizations already assess nature risk of countries or provide frameworks for nature risk reporting. Specifically and most popular, the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) and the Taskforce on Nature-related Financial Disclosures (TNFD). The NGFS provides the biophysical and economic models that allow central banks to simulate what happens to their national GDP, inflation, and debt in different climate and nature risk scenarios. It provides forecasts computed with many different models for very specific topics and problems. However, NGFS doesn't act as a rating agency and these forecasts are based on critical model assumptions and rely on complex high quality data, requiring a certain degree of caution when using the data for risk assessment (Bearpark, 2025). The TNFD also does not provide country nature risk assessments but it provides a framework indicating what to disclose and the LEAP approach that describes how to do risk assessment. While the LEAP approach originally was designed for companies, it can also be adapted for sovereign debt assessment (Nature Finance, 2023). The first steps are to identify and map the ecological resources of a country and to evaluate how much it depends on these resources. We will build on this approach in our empirical analysis that closes an important gap in the literature.

To the best of our knowledge, our study is the first that considers countries' nature risk levels while we analyze the effects and channels of nature risk mitigation measures. Our study first conducts a risk assessment based on the LEAP approach and classifies countries into 5 categories based on their nature risk position. Specifically, the scores of each country in terms of ecosystem dependency and ecological budget (calculated as the difference between a nation's biocapacity and ecological footprint) are taken as measures to derive a particular country's nature risk position.

An active nature risk management approach would try to mitigate the climate crisis and reduce the dependency on ecosystem services and/or increase ecosystem resilience by increasing biodiversity. Previous studies show that strengthening environmental regulations, fostering green finance, and promoting research and technological development are promising measures for these purposes (Frohm et al., 2023; Li et al., 2022; Horn et al., 2026; Rennings, 2000). However, the joint role of these measures is hardly analyzed and it is unclear whether the effect of these measures is similar among countries with different nature risk (Iqbal et al., 2025). This work aims to fill this gap in the literature and advances prior works by examining the joint impact of environmental policy stringency, technological innovation, and green bonds issuance on ecosystem service dependency, ecological budget, biocapacity, and ecological footprint while differentiating between countries' nature risk positions.

The main objectives of this study are forefold. First, to analyze countries' nature risk management and to provide a risk assessment for each nation. Second, to investigate the role of green finance, environmental policy stringency (EPS), and technological advancement in nature risk mitigation. Third, to assess the varying influences of these mitigation measures on ecosystem dependency, ecological budget, and biodiversity while accounting for the country's risk position. Fourth, to depict the channels through which nature risk is reduced and show the influence of the mitigating measures through these channels.

To achieve these objectives, this study employs a panel dataset of 45 countries for the period 2014-2021. A fixed effect model with Driscoll-Kraay standard errors is used to derive the results. The results show a positive relationship between nature risk and risks to future economic growth, measured as GDP risk. The results also show that higher green bond volumes, EPS, and higher technological advancement proxied by RnD funding can mitigate nature risk by increasing ecological budget and biodiversity while reducing the ecological footprint. More specifically, these three mitigating measures reduce nature risk through two essential channels. By increasing the share of renewable sources for energy generation and decreasing energy intensity. The results regarding the mitigation measures' effect on ecosystem dependency differ among countries with different risk position.

This study offers several contributions. First, it assesses countries' nature risks based on the LEAP approach by considering the ecological resources of a country and its dependency on these resources. Second, we advance prior studies by jointly exploring the role of green finance, technological advancement, and environmental policy in nature risk mitigation while differentiating between countries' risk positions. Third, we shed light on the channels through which these mitigation measures can influence biodiversity and the ecological budget. Fourth, we provide empirical evidence for the mitigation measures' relation with ecosystem dependency. Finally, the findings help policymakers to design appropriate policies to mitigate nature risk while increasing biodiversity, reducing the ecological footprint, and fostering economic growth.

The remainder of the paper is as follows. Section 2 presents the theoretical background and literature review. Section 3 details the data and methodology. Section 4 displays the results. The discussion is presented in section 5. Section 6 concludes and states the policy implications, limitations, and future work avenues.

## 2. Theoretical framework and literature review

### 2.1. Theoretical framework

The theoretical foundation of this study integrates three key perspectives. First, Porter's (1991) hypothesis posits that environmental regulations can stimulate industrial technological innovation. Strong environmental policies drive sustainable advancements, such as green finance, helping firms shift toward renewable energy sources. Research by Fisher-Vanden et al. (2006) and Tang and Tan (2013) demonstrates that these innovations improve energy efficiency. Furthermore, Ma et al. (2023) and Ao et al. (2023) emphasize their role in tackling climate change and accelerating the transition to cleaner energy.

Second, the institutional perspective theory suggests that firm behavior and innovation are dictated by their institutional environment. According to Welter and Smallbone (2011), government laws and policies influence a firm's commitment to eco-friendly practices, which help decrease their ecological footprint. Finally, the diffusion of innovation theory (Feng et al., 2022) argues that innovation drives economic growth and environmental sustainability. It leads to eco-friendly products and new business models that preserve the ecological budget.

In summary, we identify three key measures to mitigate nature risk from the previous literature. These are more stringent environmental policies, higher expenditures in research and development, and increased funding of environmentally friendly projects via green bonds. The detailed impacts of these mitigation measures on the ecological budget are described in detail in the following section. However, the relation between these mitigation measures and ecosystem dependency is hardly studied. We, therefore, follow an explorative approach to analyze the latter.

### 2.2. Increasing the ecological budget and biodiversity

To increase their ecological budget, countries can increase their biocapacity, reduce their ecological footprint, or both. When coupled with environmental policy, green finance can promote efforts to reduce industrial pollution (Zhang and Zhao, 2024). EPS refers to "the strictness and rigor of regulations, laws, and measures put in place by governments to address environmental challenges" (Li et al., 2022). Stringent environmental policies can manage the extraction, utilization, and disposal of resources to secure their sustainability and limit environmental damage (Wolde-Rufael and Mulat-Weldemeskel, 2021; Kartal et al., 2025; Wang et al., 2022). Hence, EPS is negatively related to countries' ecological footprint (Horn et al., 2026). Iqbal et al. (2025) reveal that sustainable finance and technological innovation contribute to decreasing environmental degradation. More specifically, Chang et al. (2022) show that there is a negative relationship between a country's green bond volume issued and the ecological footprint. While many studies focus on the relation between the mitigation measures and countries' ecological footprint, results on the drivers of biocapacity are missing. Building on these previous findings we formulate the following hypotheses.

**H1a**. A higher issued volume of green bonds increases the ecological budget by reducing the ecological footprint.

**H1b**. Higher RnD expenses increase the ecological budget by reducing the ecological footprint.

**H1c**. Stricter environmental policy increases the ecological budget by reducing the ecological footprint.

A very well studied component of countries' ecological footprint is the carbon footprint. Green finance emerged as an important factor that can decrease carbon emissions (Sadiq et al., 2024; Sampene et al., 2024; Tariq and Hassan, 2023) and carbon intensity (Huang et al., 2023). Al Mamun et al. (2022) argue that some green bonds are issued to help pollution control efforts and enhance energy efficiency. Besides green finance, EPS can reduce carbon emissions (Frohm et al., 2023; Li et al., 2022). EPS incorporates initiatives aiming to promote the use of renewable energy as well as the development of adequate infrastructure for sustainable energy sources and, ultimately, fosters the consumption of renewable energy (Yu et al., 2023; Hassan et al., 2024). Xu et al. (2022) reveal that environmental policies can decrease energy intensity, and the reason behind this is that it drives firms to strengthen innovation. Wang et al. (2025) conclude that technological innovation reduces carbon emissions. Technological innovation contributes to improving energy efficiency and optimizing operations within industries (Razmjoo et al., 2022). Innovative technologies not only enhance the efficiency of solar power and reduce its cost but also improve the ability of a nation to produce clean energy on a large scale (Gawusu and Ahmed, 2024). Therefore, renewable energy sources can help preserve the environment, whereas fossil fuels and non-renewable energy sources harm it. Hence, the quest for eco-friendly energy sources became popular as countries recognize the threats posed by fossil fuels (Solarin et al., 2018) and the need to decrease energy intensity, which represents the ratio between energy supply and gross domestic product. Renewable energy is a key factor that helps decrease greenhouse gas emissions and fosters green development (Chen and Yang, 2024). Building on these previous findings we formulate the following hypotheses.

**H2a**. A higher issued volume of green bonds reduces the carbon footprint by increasing the share of renewable energy and decreasing energy intensity.

**H2b**. Higher RnD expenses reduce the carbon footprint by increasing the share of renewable energy and decreasing energy intensity.

**H2c**. Stricter environmental policy reduces the carbon footprint by increasing the share of renewable energy and decreasing energy intensity.

As the biodiversity crisis receives more attention, environmentalists and scholars have been calling for the use of renewable and eco-friendly energy sources to combat biodiversity loss generated by fossil fuels (Arshed et al., 2024). Fossil fuels and non-green energy sources can increase mining, require infrastructure development, and increase transportation, all of which can negatively impact biodiversity (Ali et al., 2023). Zeng et al. (2024) find a close relationship between sustainable finance, natural resource exploitation, and biodiversity preservation in BRICS economies. Gao et al. (2025) show that green finance has a positive impact on urban biodiversity in China. EPS is considered being essential in preserving ecosystems and biodiversity (Javed et al., 2025). Driving technological development can enhance biodiversity and protect the environment (Rennings, 2000; Lai et al., 2017). Moreover, it has great potential to be considered a modern solution that hinders biodiversity loss and decreases the influence of climate change harm (Acemoglu et al., 2012). We, therefore, hypothesize.

**H3a**. A higher issued volume of green bonds increases biodiversity.

**H3b**. Higher RnD expenses increase biodiversity.

**H3c**. Stricter environmental policy increases biodiversity.

The study of Usman and Radulescu (2022) shows that renewable energy improves environmental quality, which in turn helps preserve biodiversity. In addition, Kakar et al. (2024) show that renewable energy plays a role in preventing the loss of biodiversity. Joof et al. (2023) reveal that renewable energy enhances biodiversity in BRICS economies. This suggests that increasing renewable energy use and decreasing energy intensity can act as channels to preserve biodiversity and mitigate nature risk. As such, it is worth investigating whether green bond issuance, EPS, and technological innovation have a positive effect on these two channels and enhance biodiversity and mitigate nature risk.

While the reviewed studies indicate a clear picture of the influence of the mitigation measures, the reality is more complex, and some barriers make nature risk mitigation difficult. First, there exists a major gap between the financial resources needed to preserve the ecosystem services and biodiversity and the funds that are currently available (Karolyi and Tobin-de la Puente, 2023; Seidl et al., 2024). Therefore, it is unclear whether green finance can already exert an efficient influence on biodiversity (Gao et al., 2025). Second, some scholars found differing results regarding the influence of EPS and technological innovation. For instance, the findings of Demiral et al. (2021) show that more stringent environmental policies do not address environmental issues but rather augment them in both the high- and middle-income subsamples of OECD economies. In addition, Dogan et al. (2023) found that environmental taxes have a negative influence on sustainability. The effects of technological innovation are also not clear cut. Adebayo and Kirikkaleli (2021) show that GDP growth, technological innovation, and globalization increase carbon emissions in Japan, while renewable energy decreases these emissions in the short and medium run. Dauda et al. (2019) found that innovation increased carbon emissions in seven MENA countries. Wang and Wei (2020) show that technological development can lead to higher carbon emissions due to more stringent environmental policies in developing economies, which is known as the "green paradox". We therefore analyze the above stated hypotheses for subsamples of countries with different nature risk to provide a possible explanation for the differing results in the literature.

## 3. Methodology, data, and variables

### 3.1. Data and variables

The study employs a panel dataset from OECD countries plus China, India, South Africa (participating partners), Argentina, Brazil, Indonesia, Thailand (countries negotiating membership), Malaysia, and Vietnam (expressed interest in membership). Iceland and Luxembourg are excluded because of the small number of inhabitants. The data period is from 2014 to 2021. Some data points, like the "GDP Risk by 2050" are forecasts up to the year 2050 that have been developed in 2023.

An overview of all variables and data sources is presented in Table 1.

### 3.2. Methodology

#### 3.2.1. Assessing country nature risk

Nature risk corresponds to a decrease in ecosystem services. The productivity of the ecological assets of country i in year t is its biocapacity ($Biocapacity_{i,t}$). The sum of all ecological assets that a country requires to satisfy its consumption and to absorb its waste is referred to a country's ecological footprint ($Footprint_{i,t}$). This includes the carbon footprint, which is a measure of a country's carbon emissions ($Footprint\_Carbon_{i,t}$). The difference between a country's biocapacity and footprint is the country's ecological budget ($EcologicalBudget_{i,t}$). We rely on data from the Global Footprint Network for the latter variables.

Many countries' footprint overshoots their biocapacity, which is why the global ecological budget is negative, i.e. humans exploit and decrease the natural reserves. These nations have used more natural resources than nature can reward. Countries with negative ecological budgets are called ecological debtors. They benefit from the biocapacity of countries with a positive ecological budget (ecological creditors), e.g., by net-importing biocapacity through trade (agricultural products) or by emitting carbon dioxide into the atmosphere that is absorbed by the ecosystem of ecological creditors.

When experiencing a local or global decrease in ecosystem services, ecological debtors might face a severe procurement problem as their demand for ecosystem services increases/stays stable while the global supply decreases. The potential consequences are more severe for countries with a higher dependency on ecosystem services since it would be more difficult for such countries to substitute them. This study uses the dependency score of Iceberg Data Lab to measure a country's dependency on ecosystem services ($DependencyScore_{i,t}$). Specifically, it is measured as the mean dependency across 26 ecosystem services weighted by segment revenues of country i in year t.

We use k-means clustering to assign countries to groups according to their dependency on ecosystem services ($DependencyGroup_{i,t}$; 0 (lowest dependency) to 2 (highest dependency)). We opt for three clusters after considering within sum of squares and its logarithm, the η2 coefficient, and the proportional reduction of error (PRE) coefficient for two to twenty cluster solutions.[1] Furthermore, we split countries into two groups according to their ecological budget ($BudgetGroup_{i,t}$; Group 0 (1) are countries with negative (positive) ecological budget). Next, we use these two group scores for assigning the countries a risk position score ($RiskPosition_{i,t}$; 0 (low risk, i.e. $BudgetGroup_{i,t} = 1$ & $DependencyGroup_{i,t} = 0$) to 4 (high risk, i.e. $BudgetGroup_{i,t} = 0$ & $DependencyGroup_{i,t} = 2$).

The IMF publishes forecasts for the net potential GDP risk of a country by 2050 from climate damage in percent of its GDP. We consider the GDP risk for three scenarios. The scenario "Current Policies" assumes that only currently implemented policies are preserved, leading to growing emissions until 2080, about 3 °C of warming, and high physical risks but no transition risk ($GDPRiskCurrent2050_i$). In the scenario "Net Zero 2050", global net zero CO2 emissions are reached around 2050 because of stringent climate policies and innovation. This scenario assumes that ambitious climate policies are introduced immediately. Physical risks are relatively low, but transition risks are high ($GDPRiskNetZero2050_i$). In the "Delayed Transition" scenario, global annual emissions do not decrease until 2030 ($GDPRiskDelayed2050_i$). Strong policies are then needed to limit warming to below 2 °C. This leads to both higher transition and physical risks than the Net Zero 2050 scenario.

In addition, we employ the Biodiversity and Habitat Sub Index ($BDH_{i,t}$) of the Environmental Performance Index (EPI) by Yale University for measuring the biodiversity of a country's ecosystem.

#### 3.2.2. Measures of nature risk mitigation

We identify three key measures to mitigate nature risk from the previous literature. These are more stringent environmental policies, higher expenditures in research and development, and increased funding of environmentally friendly projects via green bonds.

The stringency of environmental policies of country *i* in year *t* ($EPS_{i,t}$) is captured by the Environmental Policy Stringency Index. This index is retrieved from the OECD library and ranges from 0 (not stringent) to 6 (highest degree of stringency). The data series is only available until the year 2020. To derive implications for policymakers, we use the Climate Policy Score of the year 2025 ($ClimatePolicyCCPI_{i,t}$), which is part of the Climate Change Performance Index published by Germanwatch, NewClimate Institute, and Climate Action Network International. The Environmental Policy Stringency Index is strongly positively correlated with the Climate Policy Score. Therefore, the latter should be suitable to proxy environmental policy stringency, although it is only focused on the subtopic of climate policy.

In this study, we proxy technological research and innovation by Research and Development (RnD) expenses. RnD expenses can serve as an indicator for technological innovation (Albino et al., 2014). A country's domestic spending in RnD ($GDExpRnD_{i,t}$) is measured as its total expenditure on RnD as a percent of the country's GDP in year t. The data is also available from the OECD library. The volume of green bond issues per country and year is also adjusted by a country's GDP in that same year, i.e. we employ the issued green bond volume in percent of GDP of country *i* in year *t* in USD ($GBV_{i,t}$). The green bond data is from the Climate Bonds Initiative. The sum of $GDExpRnD_{i,t}$ and $GBV_{i,t}$ are the investments for the mitigation of nature risk per country and year ($InvestmentsMitigation_{i,t}$).

We use k-means clustering to assign countries to groups according to

[1] Detailed results available from the authors upon request.

**Table 1**
Variables and data sources.

| Abbreviation | Full name | Definition | Source |
|---|---|---|---|
| $BDH_{i,t}$ | Biodiversity and Habitat Index (*BDH*) | Biodiversity and Habitat Sub Index (*BDH*) of the Environmental Performance Index (EPI) by Yale University. It is computed using different weights for seven indicators as follows: Terrestrial Biome Protection (national) (22.2%), Terrestrial Biome Protection (global) (22.2%), Marine Protected Areas (22.2%), Protected Areas Rep. Index (14%), Species Habitat Index (8.3%), Species Protection Index (8.3%), Biodiversity Habitat Index (3%). The higher the index, the higher is the biodiversity and the healthier is the habitat. | Yale University, Environmental Performance Index. https://epi.yale.edu/ |
| $Biocapacity_{i,t}$ | Biocapacity per person | Biocapacity represents the productivity of its ecological assets. If not harvested, these areas can also be used to absorb the waste produced. Biocapacity is measured per person in global hectares per country *i* in year *t*. | Global Footprint Network https://www.footprintnetwork.org/our-work/ecological-footprint/ |
| $BudgetGroup_{i,t}$ | Ecological Budget Group | $BudgetGroup_{i,t} = 1$ (=0) for countries with positive (negative) $EcologicalBudget_{i,t}$. | Own calculations based on Global Footprint Network https://www.footprintnetwork.org/our-work/ecological-footprint/ |
| $ClimatePolicyCCPI_{i,t}$ | Climate Policy Score | The Climate Policy Score is part of the Climate Change Performance Index. Higher scores indicate more ambitious climate policies of country *i* in year *t*. | Climate Change Performance Index by Germanwatch, NewClimate Institute, Climate Action Network International https://ccpi.org/wp-content/uploads/CCPI-2025-Results.pdf |
| $ClimatePolicyGroup_{i,t}$ | Climate Policy Group | The indicator assigns country *i* to one of three Climate Policy Groups (1 = least ambitious to 3 = most ambitious) based on $ClimatePolicyCCPI_{i,2025}$ | Own calculations based on $ClimatePolicyCCPI_{i,t}$ |
| $DependencyGroup_{i,t}$ | Dependency group | The indicator assigns country *i* to one of three dependency groups (0 = lowest dependency to 2 = highest dependency) based on k-means-cluster analysis with $DependencyScore_{i,t}$ | Own calculations based on data from Iceberg Data Lab |
| $DependencyScore_{i,t}$ | Dependency score | The Dependency score is the mean dependency across 26 ecosystem services weighted by segment revenues of country *i* in year t. It corresponds to direct dependencies i.e. scope 1 only and ranges between 0% (no dependency on ecosystem services) to 100% (full dependency on ecosystem services). | Iceberg Data Lab |
| $EAI_{i,t}$ | Environmental Awareness Index | Measures Google search volume of more than 300 keywords per country to proxy environmental awareness of the population | Google trends and own calculations |
| $EcologicalBudget_{i,t}$ | Ecological Budget | Ecological budget is $Biocapacity_{i,t} - Footprint_{i,t}$. Countries with positive (negative) ecological budgets are called ecological creditors (debtors). | Own calculations based on Global Footprint Network https://www.footprintnetwork.org/our-work/ecological-footprint/ |
| $EnergyIntens_{i,t}$ | Energy Intensity | Represents the ratio between energy supply and gross domestic product measured at purchasing power parity | World Bank https://databank.worldbank.org/metadataglossary/world-development-indicators/series/EG.EGY.PRIM.PP.KD |
| $EPS_{i,t}$ | Environmental Policy Stringency Index | Country-specific composite index of the stringency of environmental policy | OECD https://stats.oecd.org/Index.aspx?DataSetCode = EPS |
| $Footprint_{i,t}$ | Ecological Footprint | Sum of all ecological assets that a given population requires to produce the natural resources it consumes and to absorb its waste, especially carbon emissions measured per person in global hectares per country *i* in year *t*. | Global Footprint Network https://www.footprintnetwork.org/our-work/ecological-footprint/ |
| $Footprint\_Carbon_{i,t}$ | Carbon Footprint | Measures CO2 emissions associated with fossil fuel use. | Global Footprint Network https://www.footprintnetwork.org/our-work/ecological-footprint/ |
| $GBV_{i,t}$ | Green Bond Issuance in % of GDP | Volume of Green Bond issues in percent of GDP of country *i* in year *t* in USD | Data for the volume of green bonds per year in a country in USD is retrieved from Climate Bonds Initiative. https://www.climatebonds.net/market/data/ |
| $GBVGroup_{i,t}$ | Green Bond Volume Group | The indicator assigns country *i* to one of three Green Bond Volume Groups (1 = lowest volume to 3 = highest volume) based on $GBV_{i,2022}$ | Own calculations based on data from Climate Bonds Initiative. https://www.climatebonds.net/market/data/ |
| $GDP_{i,t}$ | Gross Domestic Product per capita | Logarithmized Gross Domestic Product per capita in constant 2015 US$ | World Bank https://data.worldbank.org/indicator/NY.GDP.PCAP.KD |
| $GDExpRnD_{i,t}$ | Gross Domestic Expenditure on RandD (*GERD*) | Gross domestic spending on research and development (R&D) is the total expenditure (current and capital) on R&D in a country i as percent of the GDP in year *t*. | OECD https://www.oecd.org/en/data/indicators/gross-domestic-spending-on-r-d.html |
| $GDPRiskCurrent2050_i$ | GDP Risk by 2050, scenario “Current transition” | Net potential decrease in GDP country *i* by year 2050 caused by climate damages in percent of GDP in the Network for Greening the Financial System (NGFS) Phase 3 scenario “Current transition”. The estimation is based on data from the year 2023. | IMF https://climatedata.imf.org/pages/ngfs/#ngfs7 National Institute Global Econometric Model results; and IMF staff calculations |
| $GDPRiskDelayed2050_i$ | GDP Risk by 2050, scenario “Delayed transition” | Net potential decrease in GDP country *i* by year 2050 caused by climate damages in percent of GDP in the Network for Greening | IMF https://climatedata.imf.org/pages/ngfs/#ngfs7 |

(*continued on next page*)

**Table 1** (*continued*)

| Abbreviation | Full name | Definition | Source |
|---|---|---|---|
| | | the Financial System (NGFS) Phase 3 scenario "Delayed transition". The estimation is based on data from the year 2023. | National Institute Global Econometric Model results; and IMF staff calculations |
| $GDPRiskNetZero2050_i$ | GDP Risk by 2050, scenario "Net Zero 2050″ | Net potential decrease in GDP country $i$ by year 2050 caused by climate damages in percent of GDP in the Network for Greening the Financial System (NGFS) Phase 3 scenario "Net Zero". The estimation is based on data from the year 2023. | IMF https://climatedata.imf.org/pages/ngfs/#ngfs7 National Institute Global Econometric Model results; and IMF staff calculations |
| $InvestmentsMitigation_{i,t}$ | Investments for the mitigation of nature risk | Sum of Gross Domestic Expenditure on RandD and Volume of Green Bond issues as percent of GDP per country $i$ and year $t$, i.e. $GDExpRnD_{i,t} + GBV_{i,t}$ | Climate Bonds Initiative, OECD, and own calculations |
| $InvestmentsMitigationGroup_{i,t}$ | Investments for the mitigation of nature risk group | The indicator assigns country $i$ to one of three Investments for the mitigation of nature risk group groups (1 = lowest volume to 3 = highest volume) based on $InvestmentsMitigation_{i,2022}$ | Own calculations based on Climate Bonds Initiative and OECD data |
| $Population_{i,t}$ | Population | Population of country $i$ in year $t$ | OECD https://www.oecd.org/en/data/indicators/population.html |
| $RiskPosition_{i,t}$ | Risk Position of a country according to Ecological Budget and Dependency Score | Risk Position of a country i according to Ecological Budget and Dependency Score<br>$RiskPosition_{i,t} = 0$ if $BudgetGroup_{i,t} = 1$ & $DependencyGroup_{i,t} = 0$<br>$RiskPosition_{i,t} = 1$ if $BudgetGroup_{i,t} = 1$ & $DependencyGroup_{i,t} = 1$<br>$RiskPosition_{i,t} = 2$ if $BudgetGroup_{i,t} = 0$ & $DependencyGroup_{i,t} = 0$<br>$RiskPosition_{i,t} = 3$ if $BudgetGroup_{i,t} = 0$ & $DependencyGroup_{i,t} = 1$<br>$RiskPosition_{i,t} = 4$ if $BudgetGroup_{i,t} = 0$ & $DependencyGroup_{i,t} = 2$ | Own claculations |
| $RnDGroup_{i,t}$ | Gross Domestic Expenditure on RandD (*GERD*) Group | The indicator assigns country $i$ to one of three Gross Domestic Expenditure on RandD Groups (1 = lowest expenditures to 3 = highest expenditures) based on $GDExpRnD_{i,2022}$ | Own calculations based on data from Climate Bonds Initiative. https://www.climatebonds.net/market/data/ |
| $ShareRenewables_{i,t}$ | Share of renewable energy sources of electricity production | Share of electricity generated with bioenergy, hydropower, solar, and wind | IMF https://climatedata.imf.org/pages/mitigation#mi4 International Renewable Energy Agency (IRENA); IMF Staff Calculations |

their Climate Policy Score of the year 2025 ($ClimatePolicyGroup_{i,2025}$ with 1 = least ambitious to 3 = most ambitious) and their investments for the mitigation of nature risk of the year 2022 ($InvestmentsMitigationGroup_{i,2022}$ with 1 = lowest investments to 3 = highest investments).

These mitigation measures can decrease a country's nature risk in several ways, e.g. a reduction in a country's energy intensity ($EnergyIntens_{i,t}$ the ratio between energy supply and gross domestic product; source: World Bank) and an increase in the share of renewables in electricity generation ($ShareRenewables_{i,t}$; source: IMF) (Dabbous et al., 2025).

### 3.2.3. Controls

For capturing the environmental awareness of the population of a country $i$ in year $t$, we rely on the logarithmized Environmental Awareness Index ($EAI_{i,t}$) of Dabbous et al. (2023) (see also Horn et al., 2025; Pelster et al., 2024; Horn and Oehler, 2025). The $EAI_{i,t}$ is based on more than 300 keywords that are first translated into each country's official language and then used to gather the search volume of these keywords on Google via Google Trends. The data on Google Trends is monthly. We take the average of the twelve monthly observations to compute the yearly EAI.

The remaining control variables on a country level are the logarithmized gross domestic product per capita ($GDP_{i,t}$) in constant 2015 US $ (source: World Bank) and a country's population ($Population_{i,t}$; source: OECD).

### 3.2.4. Methods and descriptives

We report t-tests between countries with different risk position scores. We also use the described variables to estimate OLS and various panel regressions. The latter include country fixed effects and use Driscoll-Kraay standard errors, as Hausman tests, tests for multicollinearity, heteroskedasticity, and cross-sectional independence suggest that this is appropriate. The different model specifications are discussed in more detail below.

Descriptive statistics for the variables of most interest are presented in Table 2. It is important to notice that the GDPRisk variables are negative, indicating a decrease in GDP caused by climate change by 2050. The data for EPS is only available until 2020 and the data for dependency is not available for all years per country. Country-year observations with incomplete data are dropped from regression analyses.

## 4. Results

We start with regressing countries' risk position score on the forecasted GDP risk until 2050 in different scenarios. Using the IMF

**Table 2**
Descriptive statistics.

| | Mean | Std. Dev. | Min | Max | N |
|---|---|---|---|---|---|
| $Biocapacity_{i,t}$ | 3.59 | 3.72 | .10 | 15.11 | 324 |
| $DependencyScore_{i,t}$ | 10.03 | 2.44 | 5.32 | 17.76 | 183 |
| $EAI_{i,t}$ | 5.89 | 3.03 | .00 | 9.10 | 369 |
| $EcologicalBudget_{i,t}$ | −.99 | 3.34 | −7.61 | 7.44 | 279 |
| $EnergyIntens_{i,t}$ | 3.61 | 1.28 | .97 | 7.71 | 315 |
| $EPS_{i,t}$ | 2.89 | .99 | .58 | 4.89 | 191 |
| $Footprint_{i,t}$ | 4.62 | 1.83 | .97 | 8.37 | 279 |
| $Footprint\_Carbon_{i,t}$ | 2.54 | 1.24 | .44 | 6.11 | 279 |
| $GBV_{i,t}$ | .43 | .63 | .00 | 3.44 | 324 |
| $GDExpRnD_{i,t}$ | 2.00 | 1.04 | .26 | 5.21 | 304 |
| $GDPRiskCurrent2050_i$ | −18.10 | 12.49 | −68.11 | −4.39 | 340 |
| $GDPRiskDelayed2050_i$ | −11.90 | 9.48 | −55.24 | −4.52 | 340 |
| $GDPRiskNetZero2050_i$ | −8.78 | 7.77 | −43.61 | −1.57 | 340 |
| $ShareRenewables_{i,t}$ | .46 | .28 | .01 | .99 | 312 |

projection scores for the net potential decrease in GDP by 2050 under 3 different climate policy scenarios, we find a positive association between a country's nature risk position score and the projected GDP losses. It is important to notice that the dependent variables are negative, indicating a decrease in GDP caused by climate change. The results of these OLS regressions are presented in Table 3 and show that the net decrease in GDP caused by climate damages in scenario "Current Policies" gets larger among countries with higher risk position scores, with a statistical significance at the one percent level. This means that the net decrease in GDP is larger among countries with a higher risk position. Specifically, moving from risk position 0 to 4 implies a 28.5 percentage point larger GDP loss by 2050 under the Current Policies scenario. We see similar results for the scenarios "Delayed Transition" and "Net Zero 2050", however, with decreasing magnitude. The latter is not surprising since nature risk is mitigated by stringent environmental policies in the scenarios "Delayed Transition" and "Net Zero 2050", i.e. climate damages are less severe and have a smaller negative impact on countries' GDP. Moreover, these results show that our risk position measure is well related to climate change risk measures, yet it is different and more holistic as it is based on the availability of and dependency on ecosystem services. Finally, since the GDP risk calculation is based on a projection model and the analysis is cross-sectional, these results are interpreted as an association and validation evidence rather than a causal effect from nature-risk position to GDP risk.

Next, we turn to measures that are associated with a decrease in nature risk, specifically funding green projects by issuing green bonds, technological advancement through increasing RnD funding, and more stringent environmental policy. First, we focus on these measures' relation with the ecological budget. Second, we analyze whether these measures are associated with a decrease in the dependency on ecosystem services. Third, we study increases in the resilience of ecosystems by increasing biodiversity and habitat quality.

Results in Table 4 show that more green bond and RnD funding as well as a more stringent environmental policy, are correlated with an increase in the ecological budget of a country in the following year, particularly in countries with high nature risk, i.e. countries with risk position values of 3 and 4. Countries that largely depend on ecological services show the largest correlation when it comes to RnD expenditures. The results indicate that if these countries spend more money on RnD, technological improvement will occur and will help increase the ecological budget much more when compared to countries with low-risk positions that are usually characterized by higher developmental levels. For instance, in risk positions 0 and 1 we find countries like Canada and Sweden. In risk level 4, we have countries like Morocco and the Philippines that could highly benefit from larger RnD funding. When green bond funding increases by one percent of a country's GDP, the ecological budget increases by .09 to .32 ha per person.

The positive effect on the ecological budget is primarily driven by a decrease in the ecological footprint, see Table 5. When green bond funding increases by one percent of a country's GDP, the ecological footprint decreases by .08 to .28 ha per person. The results support the hypotheses H1a, H1b, and H1c. Nevertheless, we also observe a positive correlation of RnD expenses and environmental policy stringency with biocapacity among high nature risk countries. It is not surprising that environmental policy has a significant influence in countries with higher-risk positions. For instance, for a country like Canada with a low risk position, it is unlikely that more stringent environmental policies will increase biocapacity, as the country already has large spaces and has

**Table 4**
Measures to increase ecological budget.

| $RiskPosition_{i,t}$ | $EcologicalBudget_{i,t}$ | | |
|---|---|---|---|
| | (0&1) | (2) | (3&4) |
| $GBV_{i,t-1}$ | .32* | .15*** | .09*** |
| | (.13) | (.04) | (.02) |
| $GDExpRnD_{i,t-1}$ | .19 | .09 | .69*** |
| | (.17) | (.06) | (.11) |
| $EPS_{i,t-1}$ | .41** | −.11 | .62*** |
| | (17) | (.08) | (.07) |
| *Controls* | Yes | Yes | Yes |
| $\alpha$ | 138*** | −13.6* | 21.6*** |
| | (24) | (6.9) | (3.00) |
| $R^2$ | .53 | .60 | .81 |
| N | 38 | 84 | 50 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $GBV_{i,t-1}$ on $EcologicalBudget_{i,t}$ in the sample of countries where $RiskPosition_{i,t}$ is 0 or 1 with panel regressions and Driscoll-Kraay standard errors (see column (0&1)) generates a coefficient of .32 with a p-value <.10 for $GBV_{i,t-1}$ as an independent variable.

**Table 5**
Measures to increase biocapacity and to decrease ecological footprint.

| $RiskPosition_{i,t}$ | $Biocapacity_{i,t}$ | | | $Footprint_{i,t}$ | | |
|---|---|---|---|---|---|---|
| | (0&1) | (2) | (3&4) | (0&1) | (2) | (3&4) |
| $GBV_{i,t-1}$ | .04 | −.01 | .01 | −.28** | −.16*** | −.08* |
| | (.06) | (.02) | (.02) | (.10) | (.03) | (.03) |
| $GDExpRnD_{i,t-1}$ | .24 | .04 | .06** | .05 | −.05 | −.63*** |
| | (.32) | (.03) | (.03) | (.36) | (.08) | (.12) |
| $EPS_{i,t-1}$ | −.30 | −.05 | .36*** | −.70** | .07 | −.26* |
| | (.16) | (.07) | (.05) | (.20) | (.13) | (.12) |
| *Controls* | Yes | Yes | Yes | Yes | Yes | Yes |
| $\alpha$ | 68* | 6.70** | 5.47*** | −70* | 20* | −16*** |
| | (29) | (2.35) | (1.14) | (31) | (8) | (3) |
| $R^2$ | .56 | .13 | .22 | .53 | .60 | .67 |
| N | 38 | 84 | 50 | 38 | 84 | 50 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $GBV_{i,t-1}$ on $Footprint_{i,t}$ in the sample of countries where $RiskPosition_{i,t}$ is 0 or 1 with panel regressions and Driscoll-Kraay standard errors generates a coefficient of −.28 with a p-value <.05 for $GBV_{i,t-1}$ as an independent variable.

**Table 3**
Risk position and GDP risk.

| | $GDPRiskCurrent2050_i$ | $GDPRiskDelayed2050_i$ | $GDPRiskNetZero2050_i$ |
|---|---|---|---|
| $RiskPosition_{i,t}$ | −4.73*** | −3.51** | −2.81** |
| | (1.73) | (1.35) | (1.12) |
| $\alpha$ | −7.81* | −4.13 | −2.49 |
| | (4.37) | (3.42) | (2.84) |
| Adj. $R^2$ | .14 | .12 | .12 |
| N | 41 | 41 | 41 |

Notes: The table presents the estimated coefficients, standard errors figuring in parentheses, and adjusted $R^2$ for OLS regression analysis. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing countries' risk position score on the forecasted GDP risk until 2050 in the scenario "Current Policies" generates a coefficient of −4.73 with a p-value <.01.

implemented some biodiversity conservation policies. However, in riskier countries like Mexico, environmental policies will be more effective, and the government regulations can enforce laws on industries to protect biodiversity and the environment. The effect of mitigating factors on biocapacity and ecological footprint, therefore, highly depends on countries' risk positions. When looking at countries in the various risk categories, we notice that countries in risk position (0 or 1) are mostly well-developed countries with large forests or land that is not fully exploited (like Canada, Norway, and Australia). Countries in risk position 2 are highly developed countries that are not highly dependent on biodiversity and do not have a large ecological budget (like Germany, Japan, and the United Kingdom). Countries in risk positions 3 and 4 depend on natural resources and are not highly developed (like Mexico, India, and the Philippines).

When breaking down the ecological footprint into its individual components, we observe that the mitigation measures are mainly associated with a decrease in the carbon footprint, i.e. lead to a reduction in carbon emissions (see Table 6; regressions for other footprint components are not reported for the sake of clarity). The interpretation of these results reveals important patterns that are replicated across the various countries' nature risk levels as evidenced by the results of the several regressions conducted in Table 6. The parameters' estimates for the three mitigating measures show negative signs across all 3 groups and are statistically significant. Specifically, the robust pattern associated with these results shows that higher green bond issuance, stricter environmental policy and higher RnD expenditures are associated with lower carbon footprint.

These results match the findings established in prior studies showing that green finance emerged as an important factor that can decrease carbon emissions (Sadiq et al., 2024; Sampene et al., 2024; Tariq and Hassan, 2023), environmental policies can decrease carbon emissions (Tiwari et al., 2024), and technological innovation can reduce carbon emissions (Wang et al., 2025).

The reduction in the carbon footprint seems to work via two channels. First, a reduction in countries' energy intensity. Second, an increase in the share of renewables in electricity generation. Results in Table 6 show that energy intensity is associated with an increasing carbon footprint, while an increasing share of renewable energy is associated with a decrease in the carbon footprint.

Regressions with energy intensity and the share of renewable energy as dependent variables indicate that all three mitigation measures individually are correlated with lower energy intensity and a higher share of renewables in electricity generation (see Table 7). This is strong support for the hypotheses H2a, H2b, and H2c.

When analyzing the relationship between the mitigation measures and the dependency on ecosystem services, we subdivide our sample into countries with low dependency (DependencyGroup = 0) and countries with medium and high dependency (DependencyGroup = 1 and 2). Results of respective regression analyses are presented in Table 8. They indicate that an increase in RnD expenditures and green bond volume might increase the dependency on ecosystem services in countries with lower dependency. Countries will benefit from technological advancement and funding to further exploit their ecosystem by using eco-friendly techniques and producing ecological products. For instance, they can use biofarming, bioenergy plants, ecological farming, and exploit forests more to use timber for construction instead of stones. With more funding, investment increases. In lower-risk countries, more spending can lead to higher exploitation of ecological resources, they still have a margin to do so, particularly if these are developed countries with enforced stringent environmental policies. However, countries with a higher risk have to be very careful in exploiting further their ecological services since they already have a high rate of biodiversity dependence and have a risk of biodiversity loss. In contrast, more stringent environmental regulation is associated with a decrease in dependency. The latter can also be observed for countries with medium and high dependency. However, higher RnD expenses are associated with a subsequent decrease in dependency in highly dependent countries, which makes sense from a risk management perspective.

Turning to the Biodiversity and Habitat Sub Index, we do not find a significant effect of green bond funding (see Table 9). However, we find a positive correlation between environmental policy stringency and biodiversity in countries with a positive ecological budget (BudgetGroup = 1). These countries have a high biocapacity. Therefore, strict regulations should enable nature to flourish and to quickly rehabilitate. In contrast, among countries with low biocapacity (BudgetGroup = 0), probably more proactive measures are needed to regain resilient ecosystems. Hence, it seems plausible that we find a positive, statistically significant influence of RnD spending on the Biodiversity and Habitat Sub Index among both groups of countries. These results strongly support hypothesis H3b. Support for H3c is only weak while we do not finde indications that would align with hypothesis H3a.

Given the substantial empirical evidence regarding the advantages of

**Table 6**
Measures to decrease carbon Footprint.

| $RiskPosition_{i,t}$ | $Footprint\_Carbon_{i,t}$ | | | | |
|---|---|---|---|---|---|
| | (0&1) | (2) | (3&4) | (all) | (all) |
| $GBV_{i,t-1}$ | −.21*** | −.15*** | −.11*** | | |
| | (.03) | (.04) | (.02) | | |
| $GDExpRnD_{i,t-1}$ | −.22** | −.28*** | −.72*** | | |
| | (.09) | (.06) | (.14) | | |
| $EPS_{i,t-1}$ | −.20* | .08 | −.51*** | | |
| | (.08) | (.05) | (.05) | | |
| $EneryIntens_{i,t}$ | | | | .80*** | |
| | | | | (.15) | |
| $ShareRenewables_{i,t}$ | | | | | −2.11*** |
| | | | | | (.26) |
| *Controls* | Yes | Yes | Yes | Yes | Yes |
| $\alpha$ | −75*** | 3.7* | −21*** | −14** | −.06 |
| | (15) | (4.5) | (3) | (4) | (2.78) |
| $R^2$ | .75 | .67 | .73 | .44 | .37 |
| N | 38 | 84 | 50 | 279 | 269 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $GBV_{i,t-1}$ on $Footprint\_Carbon_{i,t}$ in the sample of countries where $RiskPosition_{i,t}$ is 0 or 1 with panel regressions and Driscoll-Kraay standard errors (see column (0&1)) generates a coefficient of −.21 with a p-value <.01 for $GBV_{i,t-1}$ as an independent variable.

**Table 7**
Measures to decrease energy intensity and to increase the share of renewables.

| | $EnergyIntens_{i,t}$ | | | $ShareRenewables_{i,t}$ | | |
|---|---|---|---|---|---|---|
| $GBV_{i,t-1}$ | −.22*** | | | .05*** | | |
| | (.03) | | | (.01) | | |
| $GDExpRnD_{i,t-1}$ | | −.64*** | | | .12*** | |
| | | (.06) | | | (.01) | |
| $EPS_{i,t-1}$ | | | −.44*** | | | .07*** |
| | | | (.04) | | | (.02) |
| *Controls* | No | No | No | No | No | No |
| $\alpha$ | 3.66*** | 4.82*** | 5.00*** | .45*** | .25*** | .28*** |
| | (.04) | (.12) | (.13) | (.01) | (.02) | (.04) |
| $R^2$ | .30 | .26 | .24 | .26 | .14 | .09 |
| N | 270 | 227 | 191 | 269 | 225 | 191 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $GBV_{i,t-1}$ on $EnergyIntens_{i,t}$ with panel regressions and Driscoll-Kraay standard errors generates a coefficient of −.22 with a p-value <.01 for $GBV_{i,t-1}$ as an independent variable.

**Table 8**
Measures to decrease dependency on ecosystem services.

| $DependencyGroup_{i,t}$ | $DependencyScore_{i,t}$ | |
|---|---|---|
| | (0) | (1&2) |
| $GBV_{i,t-1}$ | .31** | .22 |
| | (.09) | (.16) |
| $GDExpRnD_{i,t-1}$ | .67** | −.25** |
| | (.20) | (.06) |
| $EPS_{i,t-1}$ | −.65** | −.25** |
| | (.22) | (.09) |
| Controls | Yes | Yes |
| $\alpha$ | 31** | 19*** |
| | (10) | (3) |
| $R^2$ | .21 | .19 |
| N | 67 | 56 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $EPS_{i,t-1}$ on $DependencyScore_{i,t}$ in the sample of countries where $DependencyGroup_{i,t}$ is 0 with panel regressions and Driscoll-Kraay standard errors generates a coefficient of −.65 with a p-value <.05 for $EPS_{i,t-1}$ as an independent variable.

**Table 9**
Measures to increase the Biodiversity and Habitat Sub Index.

| $BudgetGroup_{i,t}$ | $BDH_{i,t}$ | |
|---|---|---|
| | (1) | (0) |
| $GBV_{i,t-1}$ | 1.23 | −.03 |
| | (.95) | (.38) |
| $GDExpRnD_{i,t-1}$ | 7.76*** | 4.87** |
| | (1.92) | (1.58) |
| $EPS_{i,t-1}$ | 4.53** | −.60 |
| | (1.31) | (.49) |
| Controls | Yes | Yes |
| $\alpha$ | 792*** | −50 |
| | (118) | (29) |
| $R^2$ | .78 | .31 |
| N | 38 | 116 |

Notes: The table presents the estimated coefficients, Driscoll-Kraay standard errors figuring in parentheses, and $R^2$ for panel regression analysis with country-fixed effects. The symbols ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively. Example: Regressing $GDExpRnD_{i,t-1}$ on $BDH_{i,t}$ in the sample of countries where $BudgetGroup_{i,t}$ is 1 with panel regressions and Driscoll-Kraay standard errors generates a coefficient of 7.76 with a p-value <.01 for $GDExpRnD_{i,t-1}$ as an independent variable.

**Table 10**
Differences in mitigating measures between low- and high-nature-risk countries.

| | $GBV_{i,t-1}$ | $GDExpRnD_{i,t-1}$ | $EPS_{i,t-1}$ |
|---|---|---|---|
| $RiskPosition_{i,t} = 0\|1\|2$ | .57 | 2.17 | 3.17 |
| | (.44) | (.90) | (.96) |
| $RiskPosition_{i,t} = 3\|4$ | .25 | 1.47 | 2.44 |
| | (.32) | (1.12) | (.73) |
| Diff | .32*** | .71** | .73** |

Notes: The table presents, mean values and standard values (in parentheses) of $GBV_{i,t-1}$, $GDExpRnD_{i,t-1}$, and $EPS_{i,t-1}$ for countries with $RiskPosition_{i,t}$ of 0, 1, 2 and countries with $RiskPosition_{i,t}$ of 3,4 and results of t-tests between these two groups of countries. The symbols ***, **, and * indicate statistical significance of the difference between the two groups at the 1%, 5%, and 10% levels, respectively. Example: The mean $GBV_{i,t-1}$ of countries with $RiskPosition_{i,t}$ of 0, 1, 2 is .57 with a standard deviation of .44. The mean $GBV_{i,t-1}$ of countries with $RiskPosition_{i,t}$ of 3, 4 is .25 with a standard deviation of .32. The difference between these two groups of countries is .32. According to a *t*-test, this difference is significant at the 1% level.

high green bond and RnD funding as well as more stringent environmental policy, one would assume that countries with high nature risk use these measures to decrease their nature risk position. However, the results of the *t*-test in Table 10 comparing countries with low- and medium-risk positions with countries with high-risk positions show that countries with high-risk positions use these measures to a significantly lesser extent. This is a strong indication that countries with a lower nature risk are managing this risk more actively and more strongly. As a result, the gap between high-risk and low-risk countries in terms of unmanaged risk is likely to widen in the future.

## 5. Discussion

Althought the results of the empirical analysis indicate significant relations, there are some limitations that need to be considered when interpreting these results. First, some important time-varying confounders, such as structural economic change, trade openness, political institutions, or resource booms, may simultaneously affect green bond issuance, RnD spending, EPS, and ecological outcomes. Furthermore, some of our independent variables may be temporarily correlated, e.g., green bond market development and environmental awareness as well as EPS and RnD spending. Therefore, we are careful with causal claims and state that the results should be interpreted as strong conditional correlations consistent with - but not definitively proving - the proposed mechanisms.

Assuming that at least some of the identified relations hold in reality, we turn to the implications of these relations for individual countries. For a clear presentation of countries' investments in mitigation measures and climate policy, we rely on the respective groups based on k-means cluster analyses. The respective statistics are presented in Table 11.

Countries with $RiskPosition = 0$ and $RiskPosition = 1$ have the lowest pressure for nature risk management. This may provide an explanation as to why none of the respective countries demonstrate both high investments in mitigation measures and stringent climate policies. However, given the considerable challenges that climate change and biodiversity loss will present, even these countries should engage in nature risk management. The protection of their natural resources should be a compelling proposition for these nations, given that biocapacity and biodiversity represent the most valuable reserves. However, it is concerning that Canada, Sweden, Argentina, Australia, Finland, and New Zealand have adopted climate policies that are not as ambitious as would be required. Furthermore, Argentina, Australia, and New Zealand have particularly low levels of funding allocated to mitigation measures. The risk of these three nations progressing too slowly with the green transition is very high. This is of particular concern given the vital importance of these countries in the conservation of species, as a failure to do so could have catastrophic consequences. Consequently, it is imperative that these nations expeditiously reinforce their environmental and climate policies.

Countries classified as $RiskPosition = 2$ are characterised by high levels of development, yet these nations face limitations in terms of their biocapacity, resulting in an ecological footprint that exceeds their capacity to sustain it. It appears that the majority of these nations have recognised the threat posed by this situation and are willing to take measures to address it. Numerous countries have demonstrated a commitment to mitigating the risks identified, evidenced by substantial investments in mitigation measures, the implementation of stringent climate policies, or a combination of both. Notable exceptions include Ireland, Italy, Japan, Slovakia, and Switzerland (and, it could be argued, the United States, were environmental policies to be rendered redundant by the Trump presidency). It is recommended that policymakers in Ireland consider increasing the investment in mitigation measures. In the case of Japan and Switzerland, there is a necessity for the enhancement of their respective climate policies. The policy-makers in

**Table 11**
Countries nature risk position and mitigating measures.

| *RiskPosition* | Country | *GBVGroup* | *RnDGroup* | *InvestmentsMitigationGroup* | *ClimatePolicyGroup* |
|---|---|---|---|---|---|
| 0 | Canada | 2 | 2 | 2 | 1 |
| 0 | Sweden | 3 | 3 | 3 | 1 |
| 1 | Argentina | 1 | 1 | 1 | 1 |
| 1 | Australia | 1 | 2 | 1 | 1 |
| 1 | Brazil | 1 | | | 3 |
| 1 | Finland | 3 | 3 | 3 | 1 |
| 1 | Latvia | 1 | 1 | 1 | 2 |
| 1 | New Zealand | 2 | 1 | 1 | 1 |
| 1 | Norway | 3 | 2 | 2 | 2 |
| 2 | Austria | 2 | 3 | 3 | 3 |
| 2 | Belgium | 3 | 3 | 3 | 2 |
| 2 | Denmark | 3 | 3 | 3 | 3 |
| 2 | France | 3 | 2 | 2 | 2 |
| 2 | Germany | 3 | 3 | 3 | 3 |
| 2 | Ireland | 3 | 1 | 1 | 2 |
| 2 | Italy | 2 | 1 | 1 | 1 |
| 2 | Japan | 1 | 3 | 2 | 1 |
| 2 | Netherlands | 3 | 2 | 3 | 3 |
| 2 | Portugal | 3 | 2 | 2 | 3 |
| 2 | Singapore | 3 | 2 | 2 | |
| 2 | Slovakia | 2 | 1 | 1 | 1 |
| 2 | Switzerland | 1 | 3 | 2 | 1 |
| 2 | United Kingdom | 2 | 3 | 2 | 3 |
| 2 | United States | 1 | 3 | 2 | 3 |
| 3 | Chile | 3 | 1 | 1 | 2 |
| 3 | Colombia | 1 | 1 | 1 | 3 |
| 3 | Czechia | 2 | 2 | 2 | 1 |
| 3 | Greece | 2 | 1 | 1 | 2 |
| 3 | Hungary | 3 | 1 | 2 | 1 |
| 3 | South Korea | 2 | 3 | 3 | 1 |
| 3 | Lithuania | 2 | 1 | 1 | 2 |
| 3 | Mexico | 1 | 1 | 1 | 2 |
| 3 | Poland | 1 | 1 | 1 | 1 |
| 3 | Slovenia | 1 | 2 | 1 | 2 |
| 3 | South Africa | 1 | 1 | 1 | 3 |
| 3 | Spain | 3 | 1 | 1 | 2 |
| 4 | China | 1 | 2 | 2 | 3 |
| 4 | India | 1 | | | 3 |
| 4 | Indonesia | 1 | | | 2 |
| 4 | Malaysia | 1 | | | 1 |
| 4 | Morocco | 1 | | | 3 |
| 4 | Philippines | 1 | | | 3 |
| 4 | Thailand | 1 | | | 2 |
| 4 | Türkiye | 1 | 1 | 1 | 1 |
| 4 | Vietnam | 1 | | | 3 |

Italy and Slovakia must address both issues.

Among countries classified as *RiskPosition* = 3, the funding allocated to RnD is inadequate, thereby impeding their pursuit of a green transformation (with the notable exception of South Korea). In Chile, Hungary and Spain, efforts are being made to compensate for this shortfall through the issuance of green bonds. Nevertheless, the allocated amounts are inadequate to sufficiently finance the requisite mitigation measures. This situation is further exacerbated in Hungary due to the country's lack of an ambitious climate policy. A similar weak climate policy is observed in the case of Czechia, South Korea, and Poland. It is surprising that the governments of these countries are allowing the erosion of the foundation of a substantial share of their economy, given their dependency on ecosystem services.

It appears that the governments of the majority of countries facing the highest nature risk have recognised the severity of the threat. The majority of nations categorised as *RiskPosition* = 4 have adopted comprehensive climate policies (with notable exceptions being Malaysia and Türkiye). However, our analysis clearly reveals a salient issue within this category. The funding of mitigation measures, through both green bonds and gross expenditures on RnD, is inadequate. It is imperative that policy makers and financial authorities in these countries create the circumstances that private sector financing can fill this funding gap. These results align with Karolyi and Tobin-de la Puente (2023) and Seidl et al. (2024), who advocate that a major gap still exists between the financial resources needed to preserve biodiversity and the funds that are currently available. However, they advance prior findings by specifically showing which countries suffer from a more severe funding gap, and this depends on the nature risk position of each economy.

In general, our analysis revealed that several countries with high biocapacity and biodiversity have to implement more stringent environmental protections to mitigate the global risk of species extinction and loss of natural services. These countries also lack the necessary funding needed to ensure the implementation of the mitigation measures.

The countries of Colombia, Chile, Mexico, South Africa, China, India, Indonesia, Morocco, the Philippines, Thailand, and Vietnam introduced stringent environmental policies but lack funding for mitigation measures. This is a severe problem. Fig. 1 shows the aggregate contribution of an area to the global distribution of species of mammals, birds, amphibians, crabs, crayfish, and shrimps. Areas highlighted in red are of the highest conservation importance. Areas in dark blue are of the least importance. All the mentioned countries cover such areas of highest conservation importance.

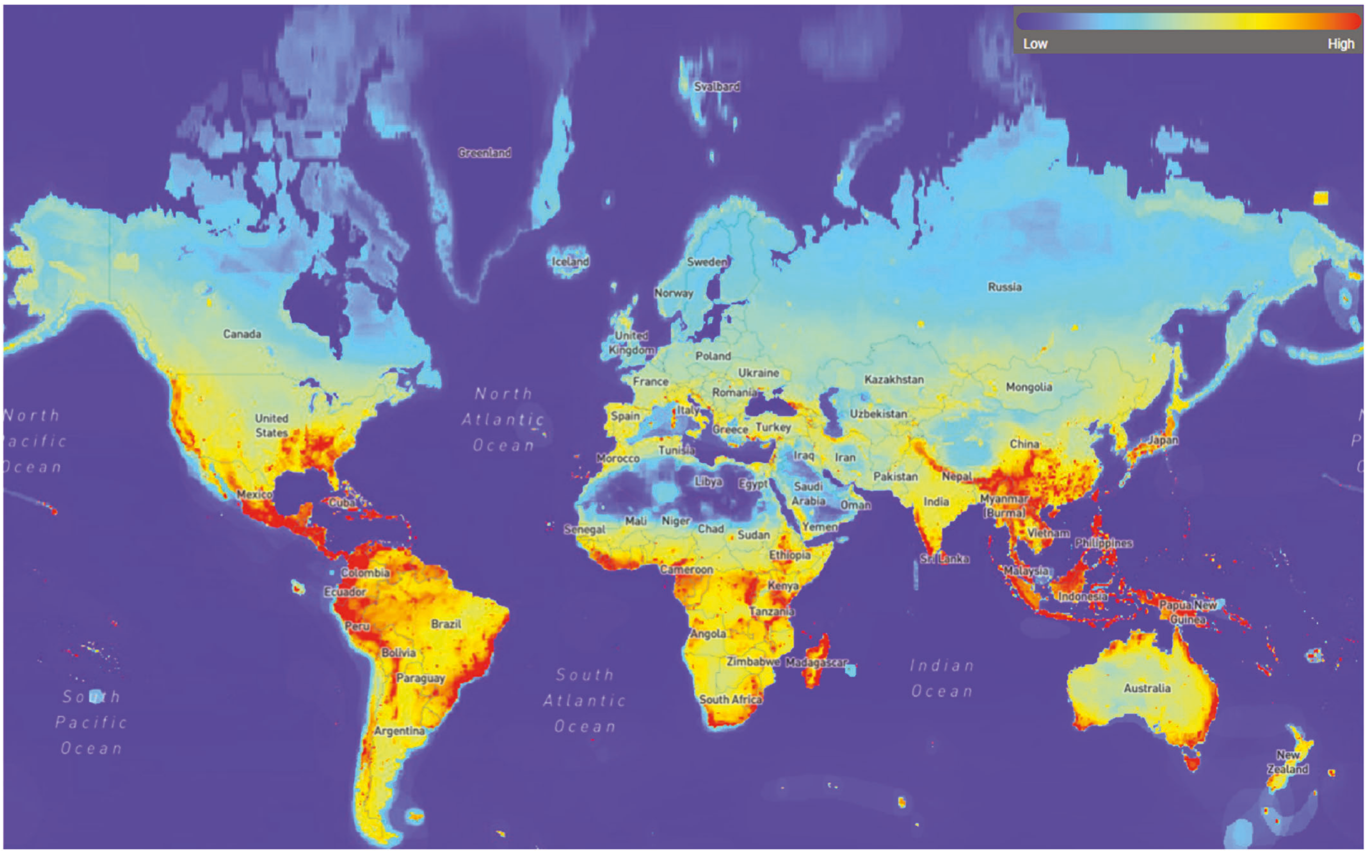


**Fig. 1.** Rarity-weighted richness for each species calculated as the contribution of an area toward the global distribution of the species.
(Source: https://www.ibat-alliance.org/).

Fig. 2 maps the STARt scores geographically. These scores indicate the potential contribution of threat reduction actions to reducing global extinction risk. Threat reduction actions in light yellow areas have a low impact on global extinction risk, whereas the impact is higher in dark green areas. The areas in Fig. 2 in which conservation measures are likely to have the greatest impact correspond closely to the areas of greatest conservation importance in Fig. 1. It is imperative that environmental protection and conservation measures be accorded the highest priority in these areas.

## 6. Conclusion and policy implications

The net decrease in GDP caused by climate damages in scenario "Current Policies" gets larger among countries with higher risk position scores, with a statistical significance at the one percent level. This result highlights the statistically significant positive association rather than the causal effect from nature-risk position to GDP risk. Countries with higher nature-risk position scores are those for which the projected GDP losses are higher under the different scenarios.

We analyze three measures for nature risk mitigation. Funding green projects by issuing green bonds, technological advancement through increasing RnD funding, and more stringent environmental policy. We find indications that these measures can increase the ecological budget by increasing biocapacitiy and decreasing the environmental footprint, specifically the carbon footprint by decreasing energy intensity and increasing the share of renewable energy sources. Furthermore, RnD funding and stringent environmental policy can decrease dependency on nature services and increase biodiversity. Therefore, the issuance of green bonds, RnD funding, and more stringent environmental policy appear suitable to mitigate nature risk. This is relevant for all countries around the world. Depending on their nature risk, countries should take suitable measures to decrease this risk.

The results also reveal that several countries with high biocapacity and biodiversity will have to implement more stringent environmental protections to mitigate their nature risk. In addition, those countries lack funding for mitigation measures.

It is therefore vital for those countries to recognize the significance of this high priority by implementing more stringent environmental policies and facilitating funding for environmental projects and RnD initiatives. Governments and policymakers should impose stricter environmental regulations on enterprises and businesses, since doing so will encourage firms to adopt clean energy sources, enhance their ability to develop eco-friendly technologies, and promote energy efficiency. One way to do so is by using environmental taxation, which represents an efficient policy instrument to decrease fossil fuel use, maintain sustainable development, and reduce ecological degradation. Governments can also promote the development of eco-friendly technologies and green innovations by imposing taxes on activities that cause harm to the environment and increase natural resource depletion. Further, the revenues collected from these taxes could be deployed to promote RnD activities established as essential to mitigate nature risk. Government and policymakers are advised to encourage firms to invest in RnD activities, facilitating the use of clean energy sources, helping to develop environmentally friendly technologies and products, and assisting in ecosystem protection. Governments can also give subsidies to support social entrepreneurs and provide grants for startups that focus on issuing or using sustainable products and technologies.

Moreover, it is crucial to provide the necessary funding needed for mitigating the global effects of climate change and biodiversity loss. A potential solution to this issue is the establishment of a nature-positive financial system, enabling funding by the private sector. Such a system must be designed on a global scale and implemented with alacrity.


**Fig. 2.** STARt Threat Abatement layer.
(Source: https://www.ibat-alliance.org/).

The identification of the precise mechanisms by which such a system might operate represents a promising avenue for future research. In addition, it is essential to strengthen the ability of the financial sector to support biodiversity preservation. This includes creating internal units within the financial institutions for biodiversity finance, incorporating biodiversity into the risk management approach, and using customized business models that answer the needs of the various sectors like agriculture, extractive industries, and manufacturing. Here comes the role of customized financial products like green bonds and green loans issued to finance biodiversity-linked projects. Specific biodiversity finance instruments, like green bonds, should be leveraged to improve the infrastructure and management systems of areas like national parks and reserves, and to provide the necessary funds required to foster transition to a low-carbon economy.

Finally, this study might suffer from some limitations. First, the number of countries is limited to 45 due to data availability. Future research could involve expanding the analysis to conduct a comparative study across several regions and more countries to better understand the interplay between green bonds, RnD, environmental policy stringency, nature risk, biodiversity, and ecological budget. Second, the data for biodiversity starts from 2014. As for environmental policy stringency, it only spans till 2020; this issue limits our ability to use more advanced econometric techniques to analyze the long-term impacts of the three considered factors on biodiversity. Future studies could examine how green bonds, RnD, and environmental policy stringency influence biodiversity over time using different empirical approaches once longer time series become available. Third, the biodiversity and ecosystem dependence are variables that use composite indices that condense complex ecological conditions and economic reliance in a single score. These metrics use aggregation methods and can rely on modeled or imputed estimates to fill data gaps. This can introduce differences in data quality and cross-country comparisons. Therefore, the results are interpreted as robust associations rather than exact causal parameters. However, despite relying on aggregate indices, the results remain informative, robust, and provide policy-relevant evidence.

## CRediT authorship contribution statement

**Matthias Horn:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amal Dabbous:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Andreas Oehler:** Writing – review & editing, Supervision, Project administration, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The authors do not have permission to share data.

## References


Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D., 2012. The environment and directed technical change. Am. Econ. Rev. 102 (1), 131–166. https://doi.org/10.1257/aer.102.1.131.

Adebayo, T.S., Kirikkaleli, D., 2021. Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools. Environ. Dev. Sustain. 23 (11), 16057–16082. https://doi.org/10.1007/s10668-021-01322-2.

Albino, V., Ardito, L., Dangelico, R.M., Petruzzelli, A.M., 2014. Understanding the development trends of low-carbon energy technologies: a patent analysis. Appl. Energy 135, 836–854. https://doi.org/10.1016/j.apenergy.2014.08.012.

Al Mamun, M., Boubaker, S., Nguyen, D.K., 2022. Green finance and decarbonization: evidence from around the world. Finance Res. Lett. 46, 102807. https://doi.org/10.1016/j.frl.2022.102807.

Ali, M., Joof, F., Samour, A., Tursoy, T., Balsalobre-Lorente, D., Radulescu, M., 2023. Testing the impacts of renewable energy, natural resources rent, and technological innovation on the ecological footprint in the USA: evidence from Bootstrapping ARDL. Resour. Policy. 86, 104139. https://doi.org/10.1016/j.resourpol.2023.104139.

Ansuategi, A., Escapa, M., 2002. Economic growth and greenhouse gas emissions. Ecol. Econ. 40 (1), 23–37. https://doi.org/10.1016/S0921-8009(01)00272-5.

Ao, Z., Fei, R., Jiang, H., Cui, L., Zhu, Y., 2023. How can China achieve its goal of peaking carbon emissions at minimal cost? A research perspective from shadow price and optimal allocation of carbon emissions. J. Environ. Manage. 325, 116458. https://doi.org/10.1016/j.jenvman.2022.116458.

Arshed, N., Anwar, A., Abbas, M., Mughal, W., 2024. Natural habitat vs human in competition for breathing space: need for restructuring clean energy infrastructure. Ecol. Econ. 220, 108177. https://doi.org/10.1016/j.ecolecon.2024.108177.

Bearpark, T., Hogan, D., Hsiang, S., 2025. Data anomalies and the economic commitment of climate change. Nature 644, E7–E11. https://doi.org/10.1038/s41586-025-09320-4.

Becker, A., Di Girolamo, F.E., Rho, C., 2025. Loan pricing and biodiversity exposure: Nature-related spillovers to the financial sector. Res. Int. Bus. Finance 75, 102724. https://doi.org/10.1016/j.ribaf.2024.102724.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., Courchamp, F., 2012. Impacts of climate change on the future of biodiversity. Ecol. Lett. 15 (4), 365–377. https://doi.org/10.1111/j.1461-0248.2011.01736.x.

Bettarelli, L., Furceri, D., Ganslmeier, M., Schiffbauer, M., 2025. The economic costs of temperature uncertainty. IMF Working Papers. https://doi.org/10.5089/9798400295119.00, 2025, 026. (Accessed 9 September 2025).

Brodie, J., Post, E., Laurance, W.F., 2012. Climate change and tropical biodiversity: a new focus. Trends Ecol. Evol. 27 (3), 145–150. https://doi.org/10.1016/j.tree.2011.09.008.

Chang, L., Taghizadeh-Hesary, F., Chen, H., Mohsin, M., 2022. Do green bonds have environmental benefits? Energy Econ. 115, 106356. https://doi.org/10.1016/j.eneco.2022.106356.

Chen, S., Yang, Q., 2024. Renewable energy technology innovation and urban green economy efficiency. J. Environ. Manage. 353, 120130. https://doi.org/10.1016/j.jenvman.2024.120130.

Costanza, R., Fisher, B., Mulder, K., Liu, S., Christopher, T., 2007. Biodiversity and ecosystem services: a multi-scale empirical study of the relationship between species richness and net primary production. Ecol. Econ. 61 (2-3), 478–491. https://doi.org/10.1016/j.ecolecon.2006.03.021.

Dabbous, A., Croutzet, A., Horn, M., 2025. Achieving energy resilience: the joint role of environmental policy stringency and environmental awareness. Res. Int. Bus. Fin. 74, 102692. https://doi.org/10.1016/j.ribaf.2024.102692.

Dabbous, A., Horn, M., Croutzet, A., 2023. Measuring environmental awareness: an analysis using google search data. J. Environ. Manage. 346, 118984. https://doi.org/10.1016/j.jenvman.2023.118984.

Dauda, L., Long, X., Mensah, C.N., Salman, M., 2019. The effects of economic growth and innovation on CO2 emissions in different regions. Environ. Sci. Pollut. Res. 26 (15), 15028–15038. https://doi.org/10.1007/s11356-019-04891-y.

Demiral, M., Akça, E.E., Tekin, I., 2021. Predictors of global carbon dioxide emissions: do stringent environmental policies matter? Environ. Dev. Sustain. 23 (12), 18337–18361. https://doi.org/10.1007/s10668-021-01444-7.

Díaz, S., Demissew, S., Carabias, J., Joly, C., Lonsdale, M., Ash, N., Larigauderie, A., Adhikari, J.R., Arico, S., Báldi, A., Bartuska, A., Baste, I.A., Bilgin, A., Brondizio, E., Chan, K., Figueroa, V.E., Duraiappah, A., Fischer, M., Hill, R., et al., 2015. The IPBES Conceptual Framework—Connecting nature and people. Curr. Opin. Env. Sust. 14, 1–16. https://doi.org/10.1016/j.cosust.2014.11.002.

Dogan, E., Hodžić, S., Šikić, T.F., 2023. Do energy and environmental taxes stimulate or inhibit renewable energy deployment in the European Union? Renew. Energy 202, 1138–1145. https://doi.org/10.1016/j.renene.2022.11.107.

Feng, Y., Lai, K.H., Zhu, Q., 2022. Green supply chain innovation: emergence, adoption, and challenges. Int. J. Prod. Econ. 248, 108497. https://doi.org/10.1016/j.ijpe.2022.108497.

Fisher-Vanden, K., Jefferson, G.H., Jingkui, M., Jianyi, X., 2006. Technology development and energy productivity in China. Energy Econ. 28 (5-6), 690–705. https://doi.org/10.1016/j.eneco.2006.05.006.

Frohm, E., D'Arcangelo, F.M., Kruse, T., Pisu, M., Sila, U., 2023. Environmental policy stringency and CO2 emissions: evidence from cross-country sector-level data. OECD Economics Department Working Papers No., 1773. https://www.oecd.org/content/dam/oecd/en/publications/reports/2023/11/environmental-policy-stringency-and-co2-emissions_a5458d2c/53ddcef7-en.pdf. (Accessed 9 September 2025).

Gao, Z., Zhao, Y., Li, L., Hao, Y., 2025. Nurturing nature: the role of green finance in reviving urban biodiversity. Q. Rev. Econ. Finance 102, 102005. https://doi.org/10.1016/j.qref.2025.102005.

Gawusu, S., Ahmed, A., 2024. Analyzing variability in urban energy poverty: a stochastic modeling and Monte Carlo simulation approach. Energy 304, 132194. https://doi.org/10.1016/j.energy.2024.132194.

Habibullah, M., Din, B., Tan, S., Zahid, H., 2022. Impact of climate change on biodiversity loss: global evidence. Environ. Sci. Pollut. Res. 29, 1073–1086. https://doi.org/10.1007/s11356-021-15702-8.

Hassan, M., Kouzez, M., Lee, J.Y., Msolli, B., Rjiba, H., 2024. Does increasing environmental policy stringency enhance renewable energy consumption in OECD countries? Energy Econ. 129, 107198. https://doi.org/10.1016/j.eneco.2023.107198.

Horn, M., Dabbous, A., Oehler, A., Göbel, F., 2026. Determinants and effects of green bond issuance: environmental awareness, ecological budget, biodiversity, oil and lithium. Ecol. Econ. 239, 108753. https://doi.org/10.1016/j.ecolecon.2025.108753.

Horn, M., Oehler, A., 2025. Attention, ESG, and retail investor stock holdings. J. Behav. Finance 1–19. https://doi.org/10.1080/15427560.2025.2522415.

Horn, M., Oehler, A., Dabbous, A., Croutzet, A., 2025. The relation between environmental awareness and stock returns. Int. Rev. Econ. Finance 103, 104383. https://doi.org/10.1016/j.iref.2025.104383.

Huang, J., An, L., Peng, W., Guo, L., 2023. Identifying the role of green financial development played in carbon intensity: evidence from China. J. Cleaner Prod. 408, 136943. https://doi.org/10.1016/j.jclepro.2023.136943.

Hudson, R., 2024. Biodiversity and risk in the financial sector. J. Sustain. Finance Account. 2, 100009. https://doi.org/10.1016/j.josfa.2024.100009.

IPBES, 2024. Biodiversity. https://www.ipbes.net/glossary-tag/biodiversity. (Accessed 6 September 2025).

Iqbal, M.A., Shaheen, W.A., Shabir, S., Ullah, U., Ionel-Alin, I., Mihut, M.I., Raposo, A., Han, H., 2025. Towards a green economy: investigating the impact of sustainable finance, green technologies, and environmental policies on environmental degradation. J. Environ. Manage. 374, 124047. https://doi.org/10.1016/j.jenvman.2025.124047.

Javed, A., Usman, M., Rapposelli, A., 2025. Transition toward a sustainable future: exploring the role of green investment, environmental policy, and financial development in the context of load capacity factor in G-7 countries. Sustain. Dev. 33 (2), 1589–1609. https://doi.org/10.1002/sd.3192.

Joof, F., Samour, A., Tursoy, T., Ali, M., 2023. Climate change, insurance market, renewable energy, and biodiversity: double-materiality concept from BRICS countries. Environ. Sci. Pollut. Res. 30 (11), 28676–28689. https://doi.org/10.1007/s11356-022-24068-4.

Kakar, S.K., Wang, J., Arshed, N., Le Hien, T.T., Abdullahi, N.M., 2024. Investigating the biodiversity conservation capability of technological innovation and FinTech. Helyon 10 (23), 10.1016/j.heliyon.2024.e4068310.1016/j.techsoc.2025.102841.

Karolyi, G.A., Tobin-de la Puente, J., 2023. Biodiversity finance: a call for research into financing nature. Finance Manag. 52 (2), 231–251. https://doi.org/10.1111/fima.12417.

Kartal, M.T., Mukhtarov, S., Kirikkaleli, D., 2025. Achieving environmental quality through stringent environmental policies: comparative evidence from G7 countries by multiple environmental indicators. Geosci. Front. 16 (1), 101956. https://doi.org/10.1016/j.gsf.2024.101956.

Khezri, M., Karimi, M.S., Khan, Y.A., Abbas, S.Z., 2021. The spillover of financial development on CO2 emission: a spatial econometric analysis of Asia-Pacific countries. Renew. Sust. Energy Rev. 145, 111110. https://doi.org/10.1016/j.rser.2021.111110.

Lai, X., Liu, J., Shi, Q., Georgiev, G., Wu, G., 2017. Driving forces for low carbon technology innovation in the building industry: a critical review. Renew. Sust. Energy Rev. 74, 299–315. https://doi.org/10.1016/j.rser.2017.02.044.

Li, Z., Kuo, Y.K., Mahmud, A.R., Nassani, A.A., Haffar, M., Muda, I., 2022. Integration of renewable energy, environmental policy stringency, and climate technologies in realizing environmental sustainability: evidence from OECD countries. Renew. Energy 196, 1376–1384. https://doi.org/10.1016/j.renene.2022.07.084.

Ma, R., Abid, N., Yang, S., Ahmad, F., 2023. From crisis to resilience: strengthening climate action in OECD countries through environmental policy and energy transition. Environ. Sci. Pollut. Res. 30 (54), 115480–115495. https://doi.org/10.1007/s11356-023-29970-z.

Mace, G., Norris, K., Fitter, A., 2012. Biodiversity and ecosystem services: a multilayered relationship. Trends Ecol. Evol. 27 (1), 19–26. https://doi.org/10.1016/j.tree.2011.08.006.

Nature Finance, 2023. Assessing Nature-Related Issues in Sovereign Debt Investment. https://www.naturefinance.net/wp-content/uploads/2023/10/AssessingNatureRelatedIssuesInSovereignDebtInvestment.pdf.

NGFS, 2023. Nature-Related financial risks: a conceptual framework to guide action by central banks and supervisors. Technical Report, Network for Greening the Financial System. https://www.ngfs.net/system/files/import/ngfs/medias/documents/ngfs_conceptual-framework-on-nature-related-risks.pdf. (Accessed 7 September 2025).

Nilsson, C., Grelsson, G., 1995. The fragility of ecosystems: a review. J. Appl. Ecol. 32 (4), 677–692. https://www.jstor.org/stable/2404808.

Nordhaus, W., 2019. Climate change: the ultimate challenge for economics. Amer. Econ. Rev. 109 (6), 1991–2014. https://doi.org/10.1257/aer.109.6.1991.

Organisation for Economic Co-operation and Development (OECD), 2019. Biodiversity: finance and the Economic and Business Case for Action, report prepared for the G7 Environment Minister's Meeting, 5-6 May 2019. https://doi.org/10.1787/a3147942-en. (Accessed 7 September 2025).

Pelster, M., Horn, M., Oehler, A., 2024. Who cares about ESG? J. Clim. Fin. 8, 100045. https://doi.org/10.1016/j.jclimf.2024.100045.

Porter, M.E., 1991. America's green strategy. Sci. Am. 264, 168. https://doi.org/10.1038/scientificamerican0491-168.
Razmjoo, A., Mirjalili, S., Aliehyaei, M., Østergaard, P.A., Ahmadi, A., Nezhad, M.M., 2022. Development of smart energy systems for communities: technologies, policies and applications. Energy 248, 123540. https://doi.org/10.1016/j.energy.2022.123540.
Rennings, K., 2000. Redefining innovation—Eco-innovation research and the contribution from ecological economics. Ecol. Econ. 32 (2), 319–332. https://doi.org/10.1016/S0921-8009(99)00112-3.
Sadiq, M., Chau, K.Y., Ha, N.T.T., Phan, T.T.H., Ngo, T.Q., Huy, P.Q., 2024. The impact of green finance, eco-innovation, renewable energy and carbon taxes on CO2 emissions in BRICS countries: evidence from CS ARDL estimation. Geosci. Front. 15 (4), 101689. https://doi.org/10.1016/j.gsf.2023.101689.
Sampene, A.K., Li, C., Wiredu, J., 2024. An outlook at the switch to renewable energy in emerging economies: the beneficial effect of technological innovation and green finance. Energy Policy 187, 114025. https://doi.org/10.1016/j.enpol.2024.114025.
Santos, A.M.C., Cianciaruso, M.V., Barbosa, A.M., Bini, L.M., Diniz-Filho, J.A.F., Faleiro, F.V., Gouveia, S.F., Loyola, R., Medina, N.G., Rangel, T.F., Tessarolo, G., Hortal, J., 2020. Current climate, but also long-term climate changes and human impacts, determine the geographic distribution of European mammal diversity. Glob. Ecol. Biogeorg. 29 (10), 1758–1769. https://doi.org/10.1111/geb.13148.
Scholes, R.J., 2016. Climate change and ecosystem services. Wiley Interdiscip. Rev. 7 (4), 537–550. https://doi.org/10.1002/wcc.404.
Seidl, A., Cumming, T., Arlaud, M., Crossett, C., van den Heuvel, O., 2024. Investing in the wealth of nature through biodiversity and ecosystem service finance solutions. Ecosyst. Serv. 66, 101601. https://doi.org/10.1016/j.ecoser.2024.101601.
Shaw, R.E., Farquharson, K.A., Bruford, M.W., Coates, D.J., Elliott, C.P., Mergeay, J., Ottewell, K.M., Segelbacher, G., Hoban, S., Hvilsom, C., Pérez-Espona, S., Ruņģis, D., Aravanopoulos, F., Bertola, L.D., Cotrim, H., Cox, K., Cubric-Curik, V., Ekblom, R., Godoy, J.A., et al., 2025. Global meta-analysis shows action is needed to halt genetic diversity loss. Nature 638 (8051), 704–710. https://doi.org/10.1038/s41586-024-08458-x.
Solarin, S.A., Al-Mulali, U., Gan, G.G.G., Shahbaz, M., 2018. The impact of biomass energy consumption on pollution: evidence from 80 developed and developing countries. Environ. Sci. Pollut. Res. 25 (23), 22641–22657. https://doi.org/10.1007/s11356-018-2392-5.
Song, Y., Wang, C., Wang, Z., 2023. Climate risk, institutional quality, and total factor productivity. Technol. Forecast. Soc. Change 189, 122365. https://doi.org/10.1016/j.techfore.2023.122365.
Swanson, T., Groom, B., 2012. Regulating global biodiversity: what is the problem? Oxford Rev. Econ. Policy. 28 (1), 114–138. https://doi.org/10.1093/oxrep/grs003.
Tang, C.F., Tan, E.C., 2013. Exploring the nexus of electricity consumption, economic growth, energy prices and technology innovation in Malaysia. Appl. Energy 104, 297–305. https://doi.org/10.1016/j.apenergy.2012.10.061.
Tariq, A., Hassan, A., 2023. Role of green finance, environmental regulations, and economic development in the transition towards a sustainable environment. J. Clean. Prod. 413, 137425. https://doi.org/10.1016/j.jclepro.2023.137425.
Tiwari, S., Mentel, G., Mohammed, K.S., Rehman, M.Z., Lewandowska, A., 2024. Unveiling the role of natural resources, energy transition and environmental policy stringency for sustainable environmental development: evidence from BRIC+ 1. Resour. Policy. 96, 105204. https://doi.org/10.1016/j.resourpol.2024.105204.
Usman, M., Radulescu, M., 2022. Examining the role of nuclear and renewable energy in reducing carbon footprint: does the role of technological innovation really create some difference? Sci. Total Environ. 841, 156662. https://doi.org/10.1016/j.scitotenv.2022.156662.
Wang, X., Iqbal, S., Amin, N., Hussain, M., Zaman, S., Khan, S., 2025. The role of government effectiveness, technological innovations, natural resource protection on carbon emissions in Gulf Cooperation Council region: a pathway for achieving sustainable development goals by 2030. J. Environ. Manag. 377, 124506. https://doi.org/10.1016/j.jenvman.2025.124506.
Wang, Z., Wang, T., Zhang, X., Wang, J., Yang, Y., Sun, Y., Gut, X., Wu, Q., Nepovimova, E., Watson, A.E., Kuca, K., 2024. Biodiversity conservation in the context of climate change: facing challenges and management strategies. Sci.Total Environ. 937, 173377. https://doi.org/10.1016/j.scitotenv.2024.173377.
Wang, H., Wei, W., 2020. Coordinating technological progress and environmental regulation in CO2 mitigation: the optimal levels for OECD countries & emerging economies. Energy Econ. 87, 104510. https://doi.org/10.1016/j.eneco.2019.104510.
Wang, Z., Yen-Ku, K., Li, Z., An, N.B., Abdul-Samad, Z., 2022. The transition of renewable energy and ecological sustainability through environmental policy stringency: estimations from advance panel estimators. Renew. Energy 188, 70–80. https://doi.org/10.1016/j.renene.2022.01.075.
Welter, F., Smallbone, D., 2011. Institutional perspectives on entrepreneurial behavior in challenging environments. J. Small Bus. Manag. 49 (1), 107–125. https://doi.org/10.1111/j.1540-627X.2010.00317.x.
Wolde-Rufael, Y., Mulat-Weldemeskel, E., 2021. Do environmental taxes and environmental stringency policies reduce CO2 emissions? Evidence from 7 emerging economies. Environ. Sci. Pollut. Res. 28 (18), 22392–22408. https://doi.org/10.1007/s11356-020-11475-8.
World Economic Forum, 2020. Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. https://www3.weforum.org/docs/WEF_New_Nature_Economy_Report_2020.pdf. (Accessed 6 September 2025).
Xu, Y., Umar, M., Kirikkaleli, D., Adebayo, T.S., Altuntaş, M., 2022. Carbon neutrality target in Turkey: measuring the impact of technological innovation and structural change. Gondwana Res. 109, 429–441. https://doi.org/10.1016/j.gr.2022.04.015.
Yu, L., Gao, X., Lyu, J., Feng, Y., Zhang, S., Andlib, Z., 2023. Green growth and environmental sustainability in China: the role of environmental taxes. Environ. Sci. Pollut. Res. Int. 30 (9), 22702–22711. https://doi.org/10.1007/s11356-022-23355-4.
Zeng, L., Wong, W.K., Fu, H., Mahmoud, H.A., Cong, P.T., Thuy, D.T.T., Bach, P.X., 2024. FinTech and sustainable financing for low carbon energy transitions: a biodiversity and natural resource perspective in BRICS economies. Resour. Policy. 88, 104486. https://doi.org/10.1016/j.resourpol.2023.104486.
Zhang, T., Zhao, F., 2024. A study on the relationships among green finance, environmental pollution and economic development. Energy Strategy Rev. 51, 101290. https://doi.org/10.1016/j.esr.2023.101290.