Biodiversity and firm performance: Empirical evidence in Japan

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ABSTRACT

This research investigates the relationship between biodiversity and firm value, using data of Japanese listed firms. Our database cover about 1,480 firm-year observations with full information of 355 individual firms in Japan from 2018 to 2023. We examine the effects of Corporate Biodiversity Footprint (CBF), the biodiversity loss caused by firms' business activities, on firms' financial performance measured by ROA, ROE and Tobin's Q. We find that CBF has a positive relation with ROA, indicating that firm operation benefits from natural resource exploitation. We also examine the effects of Corporate Biodiversity Dependency on firms' financial performance and find a negative relation with ROA. The collapse of the ecosystems together with increased regulations will damage firms' operating profit.

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1. Introduction

Climate change is already impacting our daily lives and will continue to do so for the foreseeable future. Yet, there is another equally important issue that has been neglected so far, named *biodiversity loss*. Biodiversity has the full form of "biological diversity" being defined as the variability among living organisms from all sources, including diversity within species, between species and of ecosystems (CBD, 1992). Humans are dependent on biodiversity, which contribute to securing safe water and food that are indispensable for our survival. On the other hand, businesses are also dependent on biodiversity for their business operation and development.

Documented in various reports, biodiversity is in crisis. Species extinction caused by humans is 1,000 times faster than the typical rate of extinction in Earth history. Although the direct drivers of biodiversity loss, such as land and sea use change, exploitation of natural resources, climate change, pollution, and the introduction of invasive alien species; activities of human can exacerbate these drivers. Direct drivers have impacts on species and ecosystems while affecting people who rely on ecosystem services for their livelihood.

Governments and global organizations increasingly raise the awareness of biodiversity loss, its impact and call for active protection via various policies in recent decades. There is a growing awareness about biodiversity among policy makers world-wide. In 2022 the Kunming-Montreal Global Biodiversity Framework (GBF) was adopted by some 200 countries which aims to halt and reverse biodiversity loss by 2030. In business, on 25 January 2024, the Global Reporting Initiative (GRI) has published "GRI 101: Biodiversity 2024" to help entities to disclose their most significant impacts on biodiversity and is effective from 1 January 2026. However, whether the private sectors, who benefit from, exploit to and impact the natural resources directly or indirectly, recognize the problems and take necessary actions is still a question. Firms doing business in the industries heavily dependent on biodiversity such as forestry, agriculture or fishery and aquaculture do not know “how much is our loss due to biodiversity collapse”. On the other hand, WEF (2020) provided the evidence that protecting and restoring natural ecosystems can lead to economic growth and create new business opportunities. The report also emphasized the important role of the private sector in maintaining sustainable nature. This research, therefore provides empirical evidence to answers the two scientific questions: *Should firms care about biodiversity risks? What is the financial impact of biodiversity loss on firm value?*

Although the interest in biodiversity increased, this research area is still very young. The link between biodiversity and finance used to receive little attention by academics due to the complexity of the topic and the lack of firm-level data on biodiversity. Firm-level data so far are achieved from secondary data provided by ESG rating agencies, such as MSCI ESG database or from primary data collected from limited firms’ sustainability reports. There is a call for more research on biodiversity finance (Karolyi and Tobin, 2023).

This research investigates the impact of biodiversity on firm value, using data of Japanese listed firms. Our paper has a strong scientific significance as we introduce novel measures of biodiversity risk as well as measures of firms’ and industries’ exposures to these risks. Our research originality of the research lies on the main variable, Corporate Biodiversity Footprint (CBF). CBF is developed by Iceberg Data Lab, a European data provider firms. The CBF aggregates the biodiversity loss caused by a firm’s annual activities related to land use, greenhouse gas (GHG) emissions, water pollution, and air pollution. To quantify the biodiversity loss caused by a specific firm, the CBF builds on the concept of Mean Species Abundance (MSA), which is endorsed by the scientific community and multilateral organizations (e.g., CBD, IPBES, and IPCC) and recommended by the UN. MSA measures the relative abundance of native species in ecosystems, compared to their abundance in undisbursed ecosystems. For example, an MSA of 0% has completely lost its native biodiversity while one with an MSA of 100% is considered equal in biodiversity to an ecosystem undisturbed by human activities.

The CBF expresses a firm's negative impacts on biodiversity in terms of square kilometers of "artificialized" or "denatured" land (i.e., km2.MSA). CBF quantifies not only the direct impact of a firm, but also the biodiversity loss along the entire value chain. Thus, the CBF contains scope 1, 2, and 3 components, whereby scope 1 measures the environmental pressure of the firm's direct activities, such as the area artificialized or occupied due to its business activity; scope 2 measures the pressures induced by the purchase of electricity, heat, and cooling; and scope 3 measures all indirect pressures (i.e., products sold or purchased, or investments made).

In details, we examine the effects of CBF and firm biodiversity dependency on firms' financial performance, proxy by ROA, ROE and Tobin's Q. We also investigate the moderating role of firms' characteristics (ex. composition of boards of directors, CSR committee existence, institutional ownership, leverage) on the relation between biodiversity and firm value. Our database cover 1,480 firm-year observations with full information of 355 individual firms in Japan from 2018 to 2023.

As far as we know, there is no existing research work in the finance area in Japan providing empirical evidence of the direct impact of biodiversity loss on firm performance. Current literature either used cross-country data or the data of the U.S., very few papers use data of the other country (Giglio et al, 2023; Flammer et al., 2023; Bassen et al., 2024; Garel et al., 2024, Kulionis et al., 2024; Coqueret et al., 2025; Li et al, 2025). Using Japan provides us several advances. *First*, Japan is one of the most biodiverse regions in the world but there is the decline of living organisms from remote islands like such as the Iriomote wildcat on Iriomote Island, the Ogasawara shrew in the Ogasawara Islands or the Yaku gecko on Yaku

Island to almost the whole of Japan, from Hokkaido to Okinawa. According to CBD (Convention on Biological Diversity), between 2007 and 2012, the number of threatened species identified in the Japanese Red List increased from 3,155 to 3,597. Indeed, the Red List identifies, as endangered species, over 20% of mammals and vascular plants, over 10% of birds and about 30% of the reptiles, amphibians and freshwater fishes. About one-third of the waterweed species in Japan are designated as threatened, and many other threatened species live in the waterside environment. Therefore, biodiversity loss preventions are a significant issue to Japan.

Second, Japan Government is very actively involved in preserving the biodiversity [1]. Various actions by the Government have been done for decades to conserve biodiversity. Ministry of Environment has released the Japan Biodiversity Outlook series named Assessment Reports 2010, 2016, and 2021, in which the importance of biodiversity is underscored. In 2023, the National Cabinet approved "National Biodiversity Strategy and Action Plan of Japan 2023–2030" on date, including the Japan's 30by30 Roadmap, which mentions the goals, "Effectively conserve and manage at least 30% of terrestrial and inland water areas, and at least 30% of marine and coastal areas by 2030". Up to now, only 20.5% of the land and 13.3% of the sea in Japan is designated as protected areas (PAs) and the country aims to expand the protected or conserved areas up to 30% to win back rich and varied blessings of nature.

Third, Japanese firms are famous for the business philosophy of Sanpo-yoshi, which prioritizes harmonious relationships with various stakeholders over profitability, including non-human stakeholder, the nature. Considering the differences in institutional background and corporate governance practices from Japan to existing countries being documented, findings

[1] https://www.cbd.int/countries/profile?country=jp

from Japan will provide new implications for countries of similar characteristics about the effects of biodiversity legislation as well as the impact of biodiversity impact on firm value.

Our main findings show that first, Japanese firms have large biodiversity footprints. However, the loss is significantly contributed from Scope 3, which indicates that firms do not directly impact the environment. Second, the greatest impact on biodiversity caused by land use and water pollution. Third, corporate biodiversity footprint has a positive relation with ROA, indicating that firm operation benefits from natural resource exploitation. Forth, there is a negative impact of Corporate Biodiversity Dependency on firms' operating performance. Japanese firms in our sample suffer from both physical risks and transition risks related to biodiversity. The collapse of the provisioning ecosystems together with increased regulations/policies introduced by regulators to mitigate biodiversity loss will damage firms' operating profit. Therefore, firms need to conserve the biodiversity in order to sustain their business in the long-term.

The remainder of the paper is structured as follows. Section 2 provides a literature review. Section 3 details the data and methodology. Section 4 presents in detail the summary statistics. Section 5 presents the empirical results and robustness check analyses. Section 6 concludes the paper.

2. Literature review

Mainstream accounting and finance journals so far are largely silent on biodiversity. Guer et al. (2024) conducted a bibliometric analysis of biodiversity in the areas of accounting, economics, and finance from 1995 to 2023 and identified 334 articles, which were mainly published in journals of environmental economics. Among the most related papers studying economic aspects of biodiversity loss, Dasgupta (2021) presents an overview of the current state of global biodiversity and the economic factors that contribute to its decline.

Regarding the body of literature on the firms' biodiversity disclosure, as far as we know, no companies have reported quantitative biodiversity outcomes related to their activities. We may have it from 2026 as this year the Global Reporting Initiative published **GRI 101: Biodiversity 2024** to help organizations disclose their biodiversity impacts. The new standard is effective from January 1, 2026. It is important to understand the motivations for firms' voluntary corporate disclosure on biodiversity, because they have a bearing on the quality of the disclosures and the extent to which various stakeholders can rely on them to make decisions.

Addison et al. (2018) assessed the top 100 of the 2016 Fortune Global 500 companies' sustainability reports to gauge the current state of corporate biodiversity accountability. The authors found that almost half (49) of the Fortune 100 mentioned biodiversity in reports, while 31 made clear biodiversity commitments, of which only 5 were specific, measurable, and time bound. Although a variety of biodiversity-related activities were disclosed (e.g., managing impacts, restoring biodiversity, and investing in biodiversity), only 9 companies provided quantitative indicators to verify the magnitude of their activities (e.g., area of habitat restored). Focusing specifically on water information disclosure, Zhang, Tang, & Huang (2021) examine the factors affecting "water-sensitive" firms' decisions to disclose water-related information. They finding that the force of country-specific disclosure legislation does not have a significant impact on the link between water disclosure and self-regulation. The highest water-using firms make public disclosures as they are already subject to mandatory disclosure regulations, moderate performers make private disclosures of partial information to specific groups of analysts and shareholders, while the weakest make none at all. Haque and Jones (2020) examined the influence of board gender diversity on a firm's biodiversity-related disclosures in European corporations from 2002 and 2016 and found that boards with females increased corporate biodiversity disclosures.

The link between biodiversity and finance has only received attention recently by academics. Most significant works were published in the last two years after the call for more research in biodiversity risks by Karolyi and Tobin-de la Puente (2022). Regarding the body of literature on investors' biodiversity pricing, literature so far provide a consistent finding that stock portfolios can be sensitive to biodiversity risk (Ma et al., 2024). Giglio et al, (2023) constructed measures of U.S. firms' biodiversity risks from a binary firm-level indicator for disclosures in 10-Ks. They found that returns covary positively with biodiversity news. Garel et al. (2024) used corporate biodiversity footprint (CBF) data to explore whether investors price this footprint. They fine a positive relationship between the CBF and stock returns following major biodiversity-related policy changes such as the Kunming Declaration and the launch of the Taskforce for Nature-related Financial Disclosures (TNFD). Bassen et al. (2024) provided evidence that strong biodiversity management is negatively associated with firms' stock price crash risk. Recently, Coqueret et al. (2025) showed that U.S. firms with a high biodiversity footprint in industries highly exposed to biodiversity-related risks exhibit higher expected returns. Research so far mainly used cross-country data or data of the U.S. firms, notably He et al. (2024) analysed the annual reports of more than 4000 Chinese companies spanning a 15-year period and revealed that substantial exposure to biodiversity risks among Chinese companies exceeded levels observed in the USA.

Regarding the body of literature on the impact of biodiversity on firms' financial performance, very few academic works exist. A working paper of Xin et al. (2023) showed no statistically significant relationship between biodiversity exposure and firm's performance measured by ROA, firm earnings and firm profit margin. On the other hand, Bach et al. (2024) documented a negative relationship. Other studies have investigated on the use of private capital to finance biodiversity conservation and restoration (see, e.g., Flammer et al., 2023).

Hoepner et al. (2023) examined infrastructure firms, demonstrating that those with more effective biodiversity risk management experience better financing conditions than peers.

No academic studies provided detailed material financial costs incurred by individual companies. We find the report of BloombergNEF illustrating the real financial costs incurred related to biodiversity. BloombergNEF (2023) profiled 10 companies that incurred financial losses as a result of poorly handled interactions with nature. The report documented that all sectors are exposed to nature risk, either physical risk or transition risk or both. For example, poultry producer Bernard Matthews lacked inadequate biosecurity measures, which enabled avian influenza to enter and spread throughout its supply chain, causing millions of pounds in lost sales and tainting its brand. This is an example of physical biodiversity risk facing by firms. On the other hand, transition risk features more prominently than physical risk, with policy and legal risk manifesting in five of the 10 cases. For example, 3M, a producer of chemicals has released toxic substances into watercourses and must pay $10.5 billion in legal liabilities. Smith et al. (2020) used 10 publicly available case studies, covering businesses of various sizes, from multiple sectors, operating in different contexts and demonstrated that business actions can contribute to the strategic goals and improve firms' value.

Overall, research on biodiversity risks and firm effects has begun to emerge in recent years. Our research is differentiated current literature in two ways. First, current literature focuses on firms in the U.S or European countries, there are few research about Asian countries; our research uses the latest firm-level biodiversity panel data of Japanese listed firms to exam the impact of biodiversity on firms' value, which will provide new findings to the related literature. Second, we not only focus on the impact but also examined the mechanism and the moderating roles of firms' characteristics. Our research illustrates detailed case studies on how companies manage these issues in their own business activities. The findings using Japanese data can be a good reference to management, investors and policy makers of the countries with similar institutional and governance characteristics.

3. Data and methodology

3.1. Data collection

We use several well-known databases in Japan to construct our research sample. Data on firm-level biodiversity is obtained from Iceberg Data Lab. This database has been used in several international publication (Garel et al., 2023). Information on firms and boards of directors is from the Director Database of Toyo Keizai (Directory of Directors) provided by Toyo Keizai Inc. Information on firm corporate governance and financial performance is from the Nikkei NEEDS Corporate Governance Evaluation System (CGES) provided by Nikkei Inc. and the Corporate Financial Databank supplied by the Development Bank of Japan. We exclude financial firms from our sample as these employ different performance measurement ratios to firms in other industries. Supplementary data sources include Nikkei Value Search, government reports, and the individual company homepages. Using these data sources, we built an unbalanced panel data for all non-financial listed firms in Japan from 2018 to 2023, of about 1,480 firm-year observations.

Our research originality of the research lies on the biodiversity variables developed by Iceberg Data Lab. We explain in details the variable creation and meaning below.

3.1.1 Corporate Biodiversity Footprint (CBF)

The Corporate Biodiversity Footprint is a measuring tool of biodiversity footprint. Footprints in an environmental context, are measures of humans' direct and indirect impact on the natural world. The impact of a commodity, company, person or community on global biodiversity, measured in terms of biodiversity change as a result of production and consumption of particular goods and services. By definition, *CBF is designed to assess the* *annual impact of activities of corporates, financial institutions, real assets and sovereign entities on global and local biodiversity*. This appraisal is based on the impact generated from the products purchased or sold by companies calculated throughout their value chain.

The CBF methodology uses the Mean Species Abundance (MSA) metric to quantify Biodiversity impact. MSA is a biodiversity metric expressing the average relative abundance of native species in an ecosystem compared to their abundance in an ecosystem undisturbed by human activities and pressures. This indicator is based on species abundance, which is the number of individuals per species, and therefore measures the conservation status of an ecosystem in relation to its original state. For instance, an area with an MSA of 0% will have completely lost its original biodiversity (or will be exclusively colonised by invasive species) whereas an MSA of 100% reflects a level of biodiversity, equal to an original, undisturbed ecosystem. This metric is endorsed by the scientific community and multilateral organizations (e.g., CBD, IPBES, and IPCC) and recommended by the UN.

CBF is an absolute metric and calculated by the four-step approach mentioned in IDL methodological guide[2]:

1. To use its physical Input/Output model Wunderpus mapping the flows and purchases of goods and services on which depend its activity and allocate the company's product flows by European 16 sector. Data is from company reports and Factset.
2. To assess and calculate each environmental pressures of the company, which will be based on its activity's mix;
3. To translate all the pressures through pressure-impact damage functions (based on GLOBIOmodel[3]) into a same biodiversity impact unit, which is Km 2. MSA;

[2] Microsoft Word - CBF client methodological guide March 23.docx

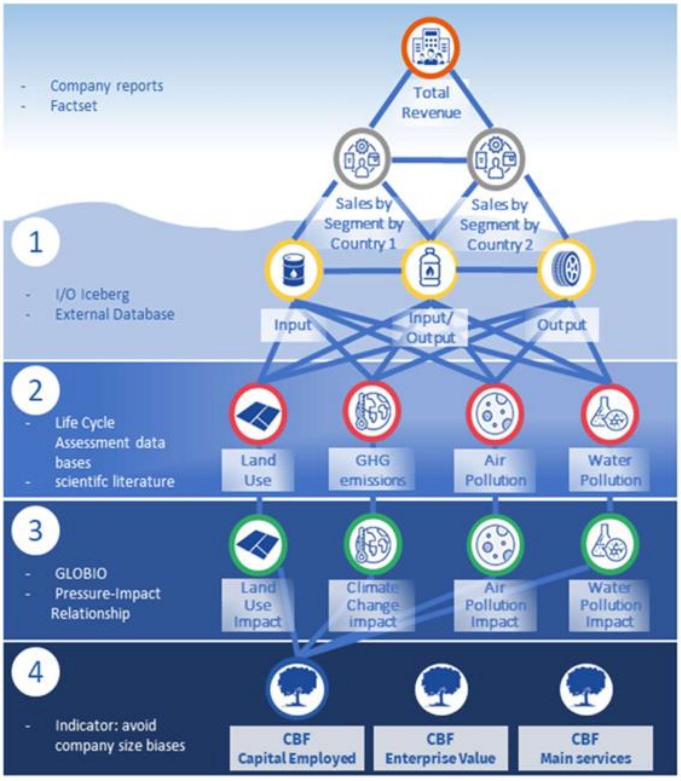
[3] The GLOBIO model expresses the response of ecosystems to anthropogenic pressures. This response is evaluated from a set of quantitative relationships and is expressed in Mean Species Abundance-MSA for each of

4. To aggregate the different impacts in an overall absolute impact.

Figure 1 below illustrate how data is processed from the modelling of commodities based on revenues over applying pressures to the calculation of the impact.

As shown in Figure 1, CBF aggregates the biodiversity loss caused by a firm's annual activities related to land use, greenhouse gas (GHG) emissions, water pollution, and air pollution. CBF is expressed in the Km².MSA unit and corresponds to a negative impact (footprint) on biodiversity (i.e. the difference between an initial and a final state of biodiversity). This unit makes the score result easily understandable by non-experts.

Figure 1: Data processing and modelling from financial data and company reports to environmental indicators. (Source: IDL)



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the pressures taken into account by the model. These pressures are climate change, atmospheric nitrogen deposition, land use, infrastructure and human encroachment. The MSA values per pressure are calculated on the basis of empirical data allowing to compare the species observed in disturbed and undisturbed reference habitats. All in all, the GLOBIO model covers six taxonomic groups: amphibians, birds, mammals, terrestrial invertebrates, reptiles, and vascular plants.

For example, -1 Km^2.MSA corresponds to the biodiversity value contained in 1Km^2 of tropical pristine forest undisturbed by human activities. A CBF of -100km2.MSA also means that 10% of the original biodiversity has been lost in an area of 1,000km2, or that a proportionally smaller amount of biodiversity, 5%, has been lost in an area of 2,000km2. In 2022, CBF value of Toyota Motor Corporation is -5,355.34 km2.MSA, which means Toyota has caused the loss of 10% of the original biodiversity in an area of 53,553km2 or 5% biodiversity loss in an area of 107,106km2. Toyota's CBF is much higher than that of Honda Motor Ltd (-2,572.20 km2.MSA), Nissan Motor Ltd (-1,554.08 km2.MSA) or Mitsubishi Motors Corporation (-493.05 km2.MSA).

It is noted that CBF quantifies not only the direct impact of a firm, but also the biodiversity loss along the entire value chain. The CBF contains scope 1, 2, and 3 components, whereby scope 1 measures the environmental pressure of the firm's direct activities, such as the area artificialized or occupied due to its business activity; scope 2 measures the pressures induced by the purchase of electricity, heat, and cooling; and scope 3 measures all indirect pressures (i.e., products sold or purchased, or investments made). Back to the example of Toyota Motor Corporation, CBF of Toyota mainly comes from the land use in its upstream value chain and the use phase of its sold vehicles. For the upstream value chain, passenger cars have a significant environmental footprint even before running due to the high amount of raw materials needed to manufacture a car (metals, rubber, plastic, glass, fiber, leather...etc). For the use phase of its sold vehicles, as most of the company's cars are powered by fossil fuels (diesel, gasoline, or LPG) they emit a lot of GHG and air pollutants (Nox and Sox) during their lifetime.

In this research, for empirical analyses, we employ eight CBF variables, namely *CBF*, *CBF scope 1, CBF scope 2, CBF scope 3, CBF GHG, CBF land* use, *CBF water pollution, and CBF air pollution*. The definition of these variables can be found in the Appendix 1.

3.1.2. Biodiversity Dependency Scores

Apart from CBF, we use another biodiversity-related variable named Biodiversity Dependency Scores also delivered by Iceberg Data Lab. This variable expresses the severity of the corporate dependency on ecosystem services – the greater the dependency the greater the incurring risks, ranging between 0% and 100%. 0% means lowest dependency and therefore lowest risk while 100% means the highest dependency and therefore highest risk. This measurement aggregates from three sub-scores which corresponding to provisioning, regulating and cultural services.

In brief, Dependency Scores assess the nature related dependencies of businesses and financial institutions through dependency on ecosystem services. Figure 2 below illustrates 26 ecosystem services used by IDL. They are categorized as provisioning, regulating, and cultural services. Definitions of 26 ecosystem services are provided in Appendix 2. Dependency scores on Provisioning and Regulating ecosystem services are measured by ENCORE[4]. Each sector's potential dependency on ecosystem services and potential impacts on natural capital assets are assessed using sector research and expert interviews. As for cultural ecosystem services, IDL calculated the scores themselves based on sector research and expert interviews as well. In this research, we employ four dependency scores, namely *Dependency Value*, *Cultural Dependency Value*, *Provisioning Dependency Value*, *Regulating Dependency Value*. The definition of these variables can be found in the Appendix 1.

[4] ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure) is a tool that can help firms assess their dependencies and impacts at a portfolio level. Developed by the ENCORE partnership consisting of Global Canopy, UNEP FI and UNEP-WCMC, ENCORE covers the entire economy and guides organisations through the early stages of their nature-positive journey. It can help financial institutions take their first steps towards understanding their dependencies and impacts on nature. https://encorenature.org/en

Figure 2: Ecosystem services covered by IDL's Biodiversity Dependency Scores (Source: IDL)

Provisioning	Regulating	Cultural
Fibers and other materials	Soil Quality	Spiritual Experience And Sense Of Place
Genetic material	Water Flow Maintenance	Information For Cognitive Development
Animal Based Energy	Water Quality	Inspiration For Culture Art Design
Surface Water	Ventilation	Recreation And Tourism
Ground Water	Maintain Nursery Habitats	Aesthetic Information
	Bio Remediation	
	Filtration	
	Dilution By Atmosphere And Ecosystems	
	Mediation Of Sensory Impacts	
	Buffering And Attenuation Of Mass Flows	
	Pest Control	
	Disease Control	
	Pollination	
	Mass Stabilization And Erosion Control	
	Climate Regulation	
	Flood And Storm Protection	

3.2. Hypotheses

With this study, we investigate the effects of biodiversity loss and corporate biodiversity dependency on firm value by using two key sets of biodiversity variables provided by Iceberg described in subsection 3.1.1 and 3.1.2. Firms' financial performance is proxy by ROA and ROE and firm value proxy by Tobin's Q.

We formulate our main research hypotheses as follows:

Hypothesis 1: Firms' CBF is negatively related to firms' performance.

Hypothesis 2: Firms' dependency to biodiversity is negatively related to firms' performance.

Our baseline panel data regressions are as follows:

$$ROA_{i,t} = \alpha + \beta_1 Dependency/CBF_{i,t} + \delta Controls_{i,t} + \varepsilon_{i,t}$$

$$ROE_{i,t} = \alpha + \beta_1 Dependency/CBF_{i,t} + \delta Controls_{i,t} + \varepsilon_{i,t}$$

$$TobinQ_{i,t} = \alpha + \beta_1 Dependency/CBF_{i,t} + \delta Controls_{i,t} + \varepsilon_{i,t}$$

Furthermore, to check the robustness of our results, we then make various sensitivity analyses with additional control variables to the baseline ones (governance and CSR variables), with lagged-1 values of biodiversity variables, with the distinction between firms manufacturing industries and non-manufacturing ones.

4. Descriptive statistics

4.1 CBF

Table 1 presents the summary statistics of the main variables used in the analysis. These are for an unbalanced panel data for 355 nonfinancial individual firms listed on several Japanese stock exchanges from 2018 to 2023. We have 200 firms for 2018, 233 firms for 2019, 346 firms for 2020, 349 firms for 2021, 311 firms for 2022. As for the year 2023, we received biodiversity data from IDL for 42 firms so far. Therefore, data of 2023 is not a full firm sample.

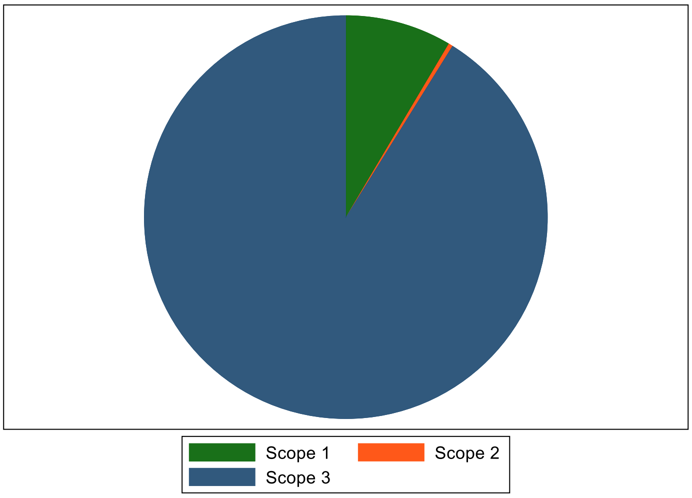
The first column lists the variable names. The mean value of CBF is 642.46km2.MSA, indicating that the average firm has a biodiversity impact corresponding to the complete loss of biodiversity over an area of 642.46 km2, which is higher than the average value of total 34 countries of 120.3km2 documented by Garel et al. (2023). Japan ranked 18th among 34 countries in term of CBF value adjusted by total assets (See Appendix 3 for details). However, the median value of CBF is 245.79km2.MSA, indicating that the average Japanese firm has a biodiversity impact corresponding to the complete loss of biodiversity over an area of 245.79 km2, which is now closer to the median value of total 34 countries of 196.4km2. One explanation for the difference in CBF mean of Japanese firms compared to the cross-country value is the size of Japanese firms included in IDL database. The mean of total assets of our firms are significantly larger than that of firms reported by Kubo and Nguyen (2021), indicating that most firms in IDL database are large Japanese corporations.

[INSERT TABLE 1 HERE]

When we decompose the CBF value based on Scope type, we find that CBF value are mainly made up by CBF Scope 3. CBF Scope 1 comes second while CBF Scope 2 is the smallest component of the total CBF. Figure 3 illustrates the decomposition of CBF in term of scope. Our finding somehow is similar to Garel et al. (2023) that Scope 3 dominates. By definition, CBF Scope 3 shows the biodiversity loss due to the firm’s indirect activities (such as its products sold or investments made, or products purchased by the firm). Scope 3 dominates indicating that most large firms do not directly impact on the environment. This metric measures the impact of a company's activities on biodiversity due to greenhouse gas emissions that occur outside of its direct control.

Indeed, CBF Scope 3 is compound of Scope 3 Upstream and Scope 3 Downstream. As shown in Table 1, the Scope 3 footprint are largely from activities upstream as mean and median CBF Scope 3 Upstream are both larger than CBF Scope 3 Downstream. CBF Scope 3 Upstream is calculated by multiplying the amount of greenhouse gases emitted by the company's upstream activities (ex. Provision of farmland or extraction of raw materials) by the biodiversity value of those emissions. CBF Scope 3 Downstream is calculated by multiplying the amount of greenhouse gases emitted by the company's products or services by the biodiversity value of those emissions. Both indicates that biodiversity loss occurs outside of firms’ direct control.

Figure 3: Decomposition of the CBF by scope type



More importantly, we find that the CBF composition of Japanese firms are different from the cross-country sample. CBF Scope 3 makes up roughly 90%, Scope 1 makes up 7% while Scope 2 makes up roughly 3%. In the 34-country sample, Scope 3 contributes about 79% to the CBF value; Scope 1 15%; Scope 2 6% correspond. Comparing with other firms world-wide, we find that although total CBF of Japanese sample is larger than the world-wide average but these firms do not directly impact on the environment that much. Their direct impact is smaller that the average world-wide value.

Similarly, we decompose the CBF into its four sources: Land use, GHG emissions, water pollution, and air pollution as shown in Figure 4. We find that the greatest impact on biodiversity loss is from land use, followed by water pollution, GHG, and air pollution. This order is different with the cross-country sample, where GHG emissions comes the second. Therefore, we suggest that Land use and Water pollution should be the focus on Japan in order to reduce biodiversity loss. The Japan 30by30 Roadmap, which aims to protect or conserve at least 30% of land and sea areas by 2030, is expected to contribute to solve this issue.

Figure 4: Decomposition of the CBF by sources of biodiversity loss

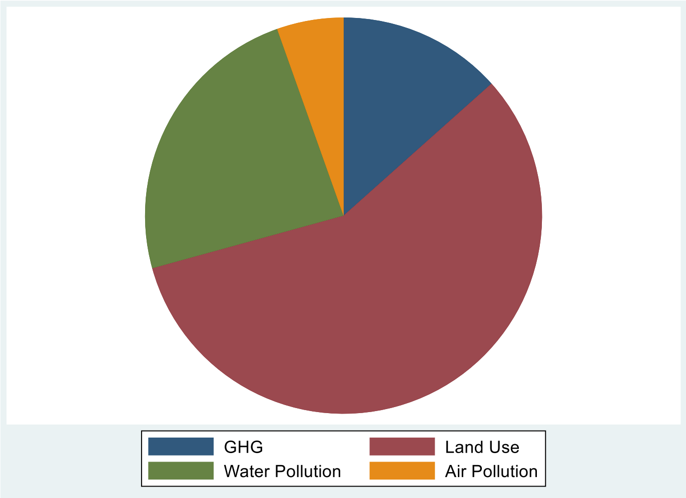
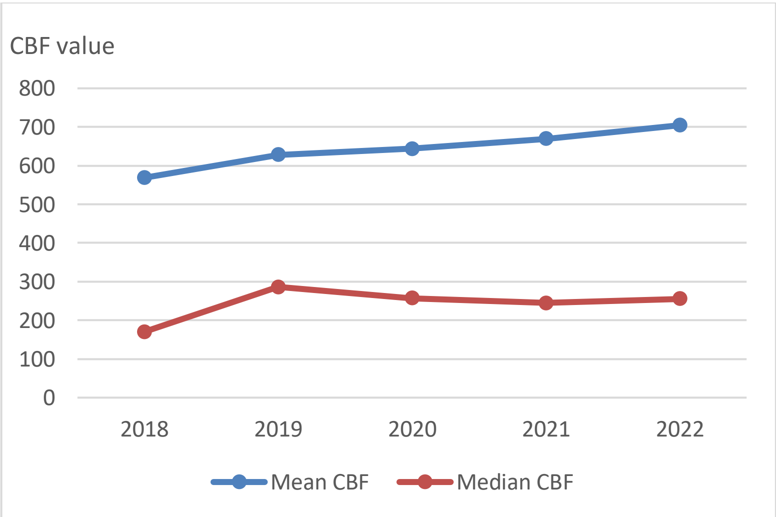


Figure 5 illustrates the yearly trend of CBF value from 2018 to 2022. Mean CBF increases gradually while median CBF started a small decline trend from 2019. In short, there is no large change in biodiversity loss caused by firms in our data sample.

Figure 5: CBF distribution by year (2018-2022)



4.2. Biodiversity dependency

Table 1 also present our second important biodiversity variable, Dependency score. The mean value of Dependency is 11.72%, indicating that on average, 11.72% of firms' business depends on the ecosystem services. Garel et al. (2023) did not tough on this variable, so we cannot make comparison. Among three components of the Dependency scores, value of

Provisioning dependency is highest, of 19.76%. This indicates that Japanese firms depend most on the provisioning ecosystem services, including surface water, ground water, genetic material and animal-based energy (details can be found in Appendix 2). In addition, the Regulating dependency is also high, of 11.91%. This indicates that Japanese firms also face with the transition risks, stemming from regulations/policies introduced by regulators to mitigate biodiversity loss.

4.3. Other firm characteristics.

Regarding other firm characteristics, on average, and as shown in Table 1, boards in Japan have ten members in average, mostly aged directors having average age of 63. Outside directors make up a significant share of the boardroom, roughly 37%. In the same vein, most board members are male, with female directors accounting for only 10% of all board positions. These firms have the institutional ownership ratio of 18% while the share of foreign shareholders is small.

In addition, we investigate the impact of biodiversity based on sectors. We divided firms into two groups: manufacturing firms and nonmanufacturing firms using TSE industry code. The univariate comparison in Table 2 shows that manufacturing firms differ substantially. Firms in manufacturing industries have higher CBF, of 777.22 km2.MSA that that of firms in other industries (473.24 km2.MSA). Regarding biodiversity dependency, manufacturing firms have higher aggregated dependency score than that of other firms, 14.15% compared with 8.32%. Score breakup show that manufacturing firms depend largely on provisioning ecosystem services (28.31%).

[INSERT TABLE 2 HERE]

As TSE industry classification is different from the industry classification used by IDL. In order to compare with the results found by Garel et al. (2023), we rank the CBF across industries (Table 3) using the industry classification provided by IDL. Lower rank values indicate larger biodiversity footprints. The top five industries having highest CBF in Japan is Tobacco, Energy, Electrical Equipment, Paper and Forest, and Beverages. This order is different from the cross-country findings, in which Retail and Wholesale tops the rank, followed by Paper and Forest, Food, Asset Management and Oil and Gas.

[INSERT TABLE 3 HERE]

5. Empirical tests

5.1 CBF and firm performance.

In this subsection, we measure the effects of CBF on firm performance using OLS with robust standard errors clustered at the firm level and fixed effects regressions. The dependent variables are ROA, ROE and Tobin's Q. The independent variable of interest is the Ln(CBF). To avoid the effects of outliers, follow Garel et a. (2023), we winsored all CBF variables at the 2.5 percent and 97.5 percent levels. We also control for board and firm characteristics by including board size, board age, outside director ratio, female director ratio, total assets (log form), leverage, foreign ownership ratio, and institutional ownership ratio as control variables. Following Adams (2016), we use firm fixed effects regression to address potential omitted variable bias caused by factors such as corporate culture and workplace practices.

Columns 1 and 2 in Table 4 present the OLS and fixed effects regression estimates of the effects of CBF on ROA. The coefficients for Ln(CBF) are positive and statistically significant in both the OLS and fixed effect regressions. Columns 3 and 4 in Table 4 provide the regression estimates of the effects of CBF on ROE. We find similar results to ROA in that the signs of the estimated coefficients are positive and significant in OLS regressions, but not FE regression. As for Tobin's Q, we find no relationship between CBF and this variable.

[INSERT TABLE 4 HERE]

The results in Table 4 thus indicate the positive impact of CBF on firms' operating performance measured by ROA. As found in Section 4, sources of CBF in Japan is largely from the devastation of land and water. We assume that these firms used extensively land and water for their business. The exploitation of the natural resources benefited firms' profit. These firms, in contrast, caused large biodiversity loss and damage the ecosystems.

5.2 Biodiversity dependency and firm performance.

In this subsection, we measure the effects of biodiversity dependency on firm performance using OLS with robust standard errors clustered at the firm level and fixed effects regressions. Similar to the previous section, the dependent variables are ROA, ROE and Tobin's Q. The independent variable of interest is the *Dependency Value* expressed in %. We also control for board and firm characteristics similarly to Table 4.

In all regressions, the coefficients for *Dependency Value* are negative in both the OLS and fixed effect regressions for all dependent variables. However, the coefficient is only statistically significant in the OLS regression for ROA, as shown in Column 1 in Table 5.

[INSERT TABLE 5 HERE]

The results in Table 5 thus indicate the negative impact of firms' biodiversity dependency on firms' operating performance measured by ROA. As found in Section 4, Japanese firms are largely dependent on provisioning ecosystem services such as ground water and surfaced water and regulating ecosystems. We assume that these firms used extensively provisioning ecosystem services for their business, especially manufacturing firms. The collapse of these ecosystems will damage firms' profit. These firms also face with the risks of intense policy and legal mandates relating to biodiversity conservations.

6. Conclusion

This research investigates the relationship between biodiversity and firm value, using data of Japanese listed firms. We find that Japanese firms have large CBF caused by land use and water pollution. Corporate biodiversity footprint has a positive relation with ROA, indicating that firm operation benefits from natural resource exploitation. We also examine the effects of Corporate Biodiversity Dependency on firms' financial performance and find a negative relation with ROA. The collapse of the ecosystems together with increased regulations will damage firms' operating profit. Therefore, firms need to conserve the biodiversity in order to sustain their business in the long-term.

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Table 1: Summary statistics

Variables	Obs.	Mean	S.D.	Median
CBF	1,482	642.46	1,004.11	245.79
CBF scope 1	1,482	45.49	107.57	5.89
CBF scope 2	1,424	2.03	3.93	0.30
CBF scope 3	1,482	579.65	936.01	216.89
CBF scope 3 Upstream	1,482	385.41	632.33	137.151
CBF scope 3 Downstream	1,212	209	462.37	29.81
CBF GHG	1,482	79.14	171.36	12.91
CBF land use	1,482	338.80	618.12	93.37
CBF water pollution	1,482	140.93	337.89	11.53
CBF air pollution	1,482	32.10	68.20	6.51
Dependency Value	1,477	11.72	6.60	12.38
Cultural Dependency Value	1,477	3.09	6.25	0.00
Provisioning Dependency Value	1,477	19.76	13.51	23.95
Regulating Dependency Value	1,477	11.91	7.66	11.25
ROA	1,478	8.50	7.48	7.22
ROE	1,478	11.04	14.01	9.97
Tobin's Q	1,457	1.88	1.89	1.25
Total assets (million yen)	1,483	13,500,000	367,000,000	732.82
Leverage (%)	1,481	46.38	18.42	46.80
Outside director ratio (%)	1,480	37.45	12.69	36.40
Female director ratio (%)	1,483	10.78	7.97	9.10
Board size (n)	1,482	10.27	2.68	10.00
Board age average	1,483	63.03	3.98	63.00
Institutional ownership (%)	1,454	18.11	7.66	17.81
Foreign ownership ratio (%)	1,483	0.05	0.98	0.00

Notes: This table provides summary statistics for all variables. The sample consists of Japanese firms listed in IDL database from 2018 to 2023, whose primary industry is not financial services. Appendix 1 details the definitions of all variables.

Table 2: Summary statistics: Industry classification

Variables	All firms			Manufacturing firms			Non-manufacturing firms		
	Obs.	**Mean**	**Median**	**Obs.**	**Mean**	**Median**	**Obs.**	**Mean**	**Median**
CBF	1,482	642.46	245.79	825	777.22	310.47	657	473.24	180.89
CBF scope 1	1,482	45.49	5.89	825	38.25	6.78	657	54.59	3.81
CBF scope 2	1,424	2.03	0.3	798	2.63	0.66	626	1.27	0.20
CBF scope 3	1,482	579.65	216.89	825	719.47	291.66	657	404.08	110.12
CBF GHG	1,482	79.14	12.91	825	97.20	17.68	657	56.47	8.42
CBF land use	1,482	338.8	93.37	825	348.77	100.22	657	326.29	85.74
CBF water pollution	1,482	140.93	11.53	825	210.76	37.55	657	53.25	1.86
CBF air pollution	1,482	32.1	6.51	825	39.81	8.45	657	22.42	4.73
Dependency Value	1,477	11.72	12.38	820	14.45	15.72	657	8.32	4.82
Cultural Dependency Value	1,477	3.09	0	820	1.58	0.00	657	4.99	1.07
Provisioning Dependency Value	1,477	19.76	23.95	820	28.31	25.07	657	9.08	2.59
Regulating Dependency Value	1,477	11.91	11.25	820	14.15	15.77	657	9.12	4.84

Notes: This table provides summary statistics for all biodiversity-related variables. The sample consists of Japanese firms listed in IDL database from 2018 to 2023, whose primary industry is not financial services. Appendix 1 details the definitions of all variables.

Table 3. The CBF: ranking by industry

Ranking number	Industry	Mean CBF
1	Tobacco	2,081.62
2	Energy	2,043.56
3	Electrical Equipment	1,932.83
4	Paper and Forest	1,829.59
5	Beverages	1,557.40
6	Food	1,219.91
7	Pharmaceutical	1,075.25
8	Chemicals	993.22
9	Power	934.10
10	Metals & Mining	821.49
11	Automotive & Logistics	794.78
12	Textiles	704.63
13	Retail and Wholesale	692.02
14	Household goods	486.58
15	Electronics	344.22
16	Construction & Real Estate	343.75
17	Industrial Equipment	342.37
18	Telecommunications	293.18
19	Transportation	249.00
20	Asset Management	216.82
21	Healthcare	139.48
22	Oil & Gas	130.03
23	Building products	77.33
24	Software	36.69
25	Leisure	34.59
26	Media	33.55
27	Hotel and accommodations	15.83
28	Internet & Data	12.06
29	Services	11.37

Table 4
Effect of Corporate Biodiversity Footprint on firm performance: OLS and fixed effects regressions.

	(1)	(2)	(3)	(4)	(5)	(6)
Regression model	OLS	Fixed effects	OLS	Fixed effects	OLS	Fixed effects
Dependent variable	ROA	ROA	ROE	ROE	Tobin's Q	Tobin's Q
Ln (CBF)	0.544*	0.421**	1.019**	0.763	0.0202	0.00171
	(0.298)	(0.199)	(0.426)	(0.496)	(0.0215)	(0.00843)
Ln (total assets)	-1.111***	-4.625***	-1.096**	-8.079***	-0.150***	-0.111***
	(0.378)	(0.963)	(0.512)	(2.395)	(0.0306)	(0.0404)
Leverage	-0.184***	-0.278***	-0.0913**	-0.710***	-0.00848***	-0.00185
	(0.0203)	(0.0282)	(0.0353)	(0.0701)	(0.00180)	(0.00120)
Board size	-0.175*	-0.0582	-0.273*	-0.179	0.000712	0.00108
	(0.0929)	(0.0851)	(0.153)	(0.212)	(0.00738)	(0.00358)
Board age average	-0.284**	0.281***	-0.490**	0.610***	-0.0242***	0.00374
	(0.129)	(0.0807)	(0.212)	(0.201)	(0.00800)	(0.00341)
Outside director ratio	0.0256	-0.00475	0.0495	-0.00149	0.00419**	-0.000613
	(0.0272)	(0.0219)	(0.0476)	(0.0544)	(0.00199)	(0.000921)
Female director ratio	0.00703	0.0195	-0.0491	-0.00134	0.00567*	0.00119
	(0.0326)	(0.0297)	(0.0481)	(0.0739)	(0.00327)	(0.00125)
Institutional ownership	0.0194	-0.126***	-0.0571	-0.303**	-0.000795	-0.00287
	(0.0396)	(0.0485)	(0.0747)	(0.121)	(0.00321)	(0.00204)
Foreign ownership ratio	-0.0485	0.0296	-0.128	-0.139	-0.00244	0.00743
	(0.0917)	(0.113)	(0.158)	(0.281)	(0.00646)	(0.00472)
Constant	46.74***	67.41***	59.38***	119.2***	3.838***	1.855***
	(9.584)	(13.53)	(15.87)	(33.65)	(0.550)	(0.568)
Observations	1,446	1,446	1,446	1,446	1,422	1,422
R-squared	0.418	0.189	0.281	0.164	0.495	0.156
Industry dummies	YES	YES	YES	YES	YES	YES
Year dummies	YES	YES	YES	YES	YES	YES

Notes: The table provides OLS and fixed effects regression estimates of the effects of CBF on firm performance. The dependent variables as shown are ROA, ROE and Tobin's Q. The independent variable of interest is natural log value of CBF. All regressions control for board and firm characteristics and industry and year effects. Robust standard errors are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Table 5
Effect of Corporate Biodiversity Dependency on firm performance: OLS and fixed effects regressions.

	(1)	(2)	(3)	(4)	(5)	(6)
Regression model	OLS	Fixed effects	OLS	Fixed effects	OLS	Fixed effects
Dependent variable	ROA	ROA	ROE	ROE	Tobin's Q	Tobin's Q
Dependency Value	-0.148**	-0.00579	-0.138	-0.0525	-0.00297	-0.00174
	(0.0609)	(0.0865)	(0.0959)	(0.215)	(0.00514)	(0.00362)
Ln (total assets)	-0.668**	-4.235***	-0.224	-7.396***	-0.134***	-0.109***
	(0.333)	(0.949)	(0.523)	(2.358)	(0.0243)	(0.0397)
Leverage	-0.177***	-0.275***	-0.0805**	-0.705***	-0.00828***	-0.00184
	(0.0186)	(0.0282)	(0.0335)	(0.0702)	(0.00176)	(0.00120)
Board size	-0.158*	-0.0608	-0.263*	-0.185	0.000905	0.00117
	(0.0882)	(0.0854)	(0.150)	(0.212)	(0.00722)	(0.00358)
Board age average	-0.267**	0.277***	-0.471**	0.599***	-0.0235***	0.00385
	(0.129)	(0.0811)	(0.212)	(0.202)	(0.00799)	(0.00342)
Outside director ratio	0.0201	-0.00526	0.0392	-0.00307	0.00415**	-0.000625
	(0.0282)	(0.0220)	(0.0498)	(0.0546)	(0.00200)	(0.000924)
Female director ratio	0.00696	0.0167	-0.0523	-0.00768	0.00557*	0.00116
	(0.0320)	(0.0298)	(0.0470)	(0.0741)	(0.00326)	(0.00125)
Institutional ownership	0.0135	-0.124**	-0.0642	-0.302**	-0.00103	-0.00280
	(0.0402)	(0.0487)	(0.0768)	(0.121)	(0.00326)	(0.00204)
Foreign ownership ratio	-0.0553	0.0412	-0.140	-0.118	-0.00261	0.00750
	(0.0898)	(0.113)	(0.153)	(0.281)	(0.00616)	(0.00472)
Constant	46.71***	64.55***	56.59***	115.1***	3.789***	1.845***
	(10.33)	(13.52)	(16.74)	(33.60)	(0.569)	(0.566)
Observations	1,442	1,442	1,442	1,442	1,418	1,418
R-squared	0.417	0.185	0.274	0.162	0.495	0.156
Industry dummies	YES	YES	YES	YES	YES	YES
Year dummies	YES	YES	YES	YES	YES	YES

Notes: The table provides OLS and fixed effects regression estimates of the effects of firms' biodiversity dependency on firm performance. The dependent variables as shown are ROA, ROE and Tobin's Q. The independent variable of interest is the biodiversity dependency value expressed in %. All regressions control for board and firm characteristics and industry and year effects. Robust standard errors are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

Appendix 1: Variable definition and data sources

Variables	**Definitions**	**Unit**	**Source**
CBF-related variables	CBF-related variables are expressed in km2. MSA, which is equivalent to the pristine natural area destroyed by the firm's annual activities. MSA is a metric characterizing the level of biodiversity in an ecosystem. The original CBF metric is a negative number, corresponding to the degradation of biodiversity caused by the firm. We multiply this variable by –1 so that higher values indicate a more negative impact on bio diversity.		
CBF	Biodiversity loss caused by the firm's annual activities. It results from four environmental pressures: land use transformation, emission of GHGs, emission of nitro gen oxides, and release of toxic compounds into the environment.	km2.MSA	IDL
CBF Scope 1	Biodiversity loss due to the firm's direct activities (i.e., surface artificialized or occupied).	km2.MSA	IDL
CBF Scope 2	Biodiversity loss due to the firm's purchase of electricity, heat, and cooling.	km2.MSA	IDL
CBF Scope 3	Biodiversity loss due to the firm's indirect activities (such as its products sold or investments made, or products purchased by the firm).	km2.MSA	IDL
CBF Scope 3 Upstream	This metric measures the impact of a company's activities on biodiversity due to greenhouse gas emissions that occur outside of its direct control. *It is calculated by multiplying the amount of greenhouse gases emitted by the company's upstream activities by the biodiversity value of those emissions.*	km2.MSA	IDL
CBF Scope 3 Downstream	This metric measures the impact of a company's activities on biodiversity due to greenhouse gas emissions that occur outside of its direct control. It includes the impact of the company's products or services on the environment during their life cycle, use and disposal. *It is calculated by multiplying the amount of greenhouse gases emitted by the company's products or services by the biodiversity value of those emissions.*	km2.MSA	IDL
CBF GHG	Biodiversity loss due to the firm's GHG emissions. In addition to direct GHG emissions due to the firm's energy consumption, GHG emissions resulting from the electricity consumption and emissions of products purchased in the firm's upstream supply chain are taken into account.	km2.MSA	IDL

CBF land use	Biodiversity loss due to the firm’s transformation of pristine land into agricultural land or artificialized areas. The firm’s direct pressures on land use, such as its physical assets, buildings, or plantations, are factored in. The land use impact of the firm’s upstream supply chain (i.e., purchased products) is also taken into account.	km2.MSA	IDL
CBF water pollution	Biodiversity loss due to the firm’s release of toxic com pounds into the water. Release of substances due to the firm’s direct activity (e.g., processing food or fertilizing crops) are taken into account, as well as those of the firm’s upstream supply chain.	km2.MSA	IDL
CBF air pollution	Biodiversity loss due to the firm’s release of nitrogen oxides (NOx) into the air. Direct pressures coming from the firm, such as NOx emissions arising from its fuel consumption, are taken into account, as are NOx emissions arising from the electricity consumption and emissions of products purchased in the firm’s up stream supply chain.	km2.MSA	IDL
Firm biodiversity dependence variables			
Dependency Value	Weighted average of the three dependency scores, reflecting a company's dependence on ecosystem services.	%	IDL
Cultural Dependency Value	Dependency score of the company on the cultural ecosystem services.	%	IDL
Provisioning Dependency Value	Dependency score of the company on the provisioning ecosystem services.	%	IDL
Regulating Dependency Value	Dependency score of the company on the regulating ecosystem services.	%	IDL
Firm performance variables			
ROA (%)	Ratio of income before tax and interest to total assets.	%	CGES
ROE (%)	Ratio of income before tax and interest to total equity	%	CGES
Tobin's Q	Ratio of total assets and total debts in book value over total market value		CGES
Control variables			CGES
Board size	Number of board members		CGES
Board age average	Average age of board members		
Outside director ratio	Percent of outside director over total board members		CGES
Female director ratio	Percent of female director over total board members		CGES
Industry dummy	33 industries classified by Tokyo Stock Exchange		CGES

Total assets	Total consolidated assets	Million yen	CGES
Leverage (%)	Ratio of sum of short-term debt and long-term debt to total assets		CGES
Foreign ownership (%)	Ratio of foreign investors' ownership to total shares		CGES
Institutional ownership (%)	Percentage of company stock held by institutional investors		CGES

Appendix 2: Definitions of 26 ecosystem services

(Source: IDL)

Provisioning
Genetic material: genetic material from plants, algae, fungi, animals or organisms.
Animal-based energy: nutrition, materials or energy from grown in-situ aquaculture, reared or wild animals for direct use or processing.
Surface Water: surface water used for nutrition, materials or energy (freshwater or marine/coastal).
Ground Water: groundwater used for nutrition, materials or energy.
Regulating
Soil quality: regulation of physical, chemical, and biological conditions of the soil.
Water flow maintenance: hydrological cycle and water flow regulation (including flood control & coastal protection).
Water quality: regulation of the chemical condition of freshwaters, including salt water, by living processes.
Ventilation: regulation of temperature and humidity, including ventilation and transpiration, for people.
Maintain nursery habitats: Providing habitats for wild plants and animals that can be useful to us.
Bioremediation: Mediation of wastes or toxic substances of anthropogenic origin by living processes.
Filtration: Filtration/sequestration/storage/accumulation of wastes by microorganisms, algae, plants, and animals.
Dilution by atmosphere and ecosystems: mediation of waste, toxins and other nuisances by non-living processes, such as freshwater ecosystems or atmosphere.
Mediation of sensory impacts: mediation of nuisances of anthropogenic origin (ie. Smell reduction, noise attenuation and visual screening).
Buffering and attenuation of mass flows: regulation of baseline flows and extreme events such as the buffering and attenuation of mass movement.
Pest control: controlling invasive species and pests.
Disease control: controlling diseases.

Pollination: seed dispersal, pollination.
Mass stabilization and erosion control: control of erosion rates.
Climate regulation: regulation of the chemical composition of the atmosphere and the oceans as well as regulation of the temperature and humidity.
Flood and storm protection: Regulation of baseline flows and extreme events.
Cultural
Spiritual experience and sense of place: natural, abiotic characteristics of nature that enable spiritual, symbolic and other interactions and elements of living systems with symbolic meaning.
Information for cognitive development: characteristics of living systems that enable scientific investigation, the creation of traditional ecological knowledge or education and training.
Inspiration for culture art design: interacting intellectually, spiritually, and symbolically with the natural environment encompasses representative engagements.
Recreation and tourism: engaging physically, experientially, intellectually, and representationally with both the natural environment and its abiotic components facilitates holistic interactions and understanding.
Aesthetic information: characteristics of living systems that enable aesthetic experiences.

Appendix 3: Country ranking by Ln (CBF/total assets) (documented from Garel et al., 2023)