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Biodiversity loss and financial stability as a new frontier for central banks: An exploration for France☆

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A B S T R A C T

As a first step to assess the financial risks associated with biodiversity loss, this paper develops a method to evaluate the exposure of the financial system to biodiversity-related - physical or transition - shocks. We apply it to the security portfolio held by French financial institutions at the end of 2019. Employing the ENCORE database, we assess physical risks by examining how the firms that issued the securities in the portfolio depend on ecosystem services to produce. Our results indicate that they significantly depend on water-related ecosystem services and that 42% of the value of securities held by French financial institutions were issued by firms highly or very highly dependent on at least one ecosystem service. Using the Global Biodiversity Score tool, we assess transition risks by quantifying the biodiversity footprint of the security portfolio and of the firms that issued the securities. We find that the portfolio footprint is equivalent to the loss of 130,000km^2 of pristine nature and that 38.5% of the portfolio value comes from firms belonging to sectors in the top 10% of biodiversity footprints. This offers new methodological tools to address the relationship between finance and biodiversity from a financial stability perspective.

1. Introduction

During the last decade, central banks have started addressing the new challenges posed by climate change to the preservation of financial stability. More recently, the Network for Greening the Financial System (NGFS), gathering more than 120 central banks and financial supervisors, acknowledged that other environmental issues could pose financial risks to individual institutions and the financial system as a whole (NGFS, 2022). In particular, biodiversity loss is increasingly perceived as a significant threat, following the alarm raised by IPBES (2019) on the worldwide deterioration of the biosphere and the services it provides - called “ecosystem services” or “nature's contribution to people” (MEA, 2005; IPBES, 2019). Like climate change, biodiversity loss could be a source of financial risks: we call the latter “biodiversity-related financial

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risks" (BRFR). On the one hand, BRFR could be the result of *physical* sources of risks emerging from the degradation of ecosystem services on which economic activities depend, such as the provision of good quality water or the protection against disease or floods. On the other hand, BRFR could emerge because of *transition* source of risks, i.e. they could result from the misalignment between firms' business model and the developments aimed toward achieving a nature-positive economy (INSPIRE and NGFS, 2022) - such as the setting up of protected areas (Johnson et al., 2021) or regulations aiming to limit nitrogen pollution (van Toor et al., 2020).[2]

The precise measurement of BRFR is impossible. Indeed, ecosystems' interactions are complex and non-linear, biodiversity is multidimensional, and the drivers of biodiversity loss are numerous and diverse,[3] calling for various and unprecedented transformations and policy interventions (IPBES, 2019). However, scenario analysis remains possible and necessary so that central banks and financial supervisors can assess how biodiversity loss or the "transformative changes" to reverse it (IPBES, 2019) could affect different economic sectors, macroeconomic variables, and the financial system. An essential step toward developing scenarios tailored to those needs consists in having a good understanding of both the dependencies and impacts of the financial system on biodiversity, via the non-financial firms it finances. Indeed, (i) assessing the dependencies of economic activities on ecosystem services, like pollination or water provisioning, can help appreciate the physical risks that could ensue if these services were disrupted; and (ii) assessing the negative impacts economic activities have on biodiversity, through land use change or pollution for example, can help understand the transition risks that could ensue if specific regulations are taken to mitigate these impacts.[4]

This paper is the first assessment of the dependencies on ecosystem services and the impacts on biodiversity of French financial institutions (FFIs) via the corporate debt securities and listed shares they held at the end of 2019. These corporate securities covered around 26% of the total amount of securities and listed shares FFIs held at the time, accounting for approximately 6% of their total assets. Following and supplementing a methodology developed by the Dutch central bank (van Toor et al., 2020), we use the ENCORE database (Natural Capital Finance Alliance, 2021) for the assessment of dependencies and the BIA-GBS tool (CDC Biodiversité, 2021) for the assessment of impacts. Then, we evaluate the portfolio value that is exposed to (i) "physically high-stake" firms, which, given their high level of dependencies on ecosystem services, could be more exposed in case of a decline in ecosystem services, and (ii) "transition high-stake" firms, which, given their high level of impacts on biodiversity, could be more exposed to changes in policies and regulations aiming to protect nature.

Our main results are the following. Regarding physical risks, we find that the portfolio of French financial institutions mainly depends on ecosystem services related to the provision of water and on the "maintenance and regulation" type of ecosystem services such as mass stabilization and erosion control, flood and storm protection, and climate regulation. The portfolio becomes at least slightly dependent on all ecosystem services when we account for the indirect dependencies of companies in the portfolio, due to the high dependencies upon ecosystem services of the firms in their supply chain. Lastly, we find that around 40% of the value of securities held by French financial institutions were issued by firms that are highly or very highly directly dependent on one ecosystem service or more - so-called "physically high-stake" firms. Regarding transition risks, we first assess the terrestrial biodiversity footprint of the portfolio. We obtain that it is comparable with the loss of at least 130,000km^2 of "pristine"[5] nature and mainly due to land-use change caused by operations from suppliers of the firms in the portfolio. Then, we define "transition high-stake" firms as firms operating in sectors with a particularly high biodiversity footprint or biodiversity intensity of their turnover. The sectors with the most significant direct impacts are agriculture, forestry, and mining. In contrast, other sectors, such as those that process food, beverages or wood products, chemicals, construction, and hotels and restaurants, significantly impact biodiversity through their value chains. As firms in the portfolio of French financial institutions are primarily located in secondary or tertiary sectors, their exposure to transition shocks appears mostly indirect: around 1/3 of the portfolio value is exposed to firms whose upstream value chain has substantial impacts on biodiversity.

Section 2 presents the rationale of the paper and the justification for focusing first on dependencies and impacts as a proxy for the exposure to biodiversity-related sources of risks and then on the exposure to high-stake firms or sectors. Section 3 describes the data and methodology used, while we investigate the results in Section 4. We discuss their meaning and potential next steps toward a full-fledged BRFR assessment in Section 5. Section 6 concludes.

2. Rationale

It is increasingly acknowledged that environmental degradation can threaten economic and financial stability (NGFS, 2019; NGFS, 2022). While the majority of the work in this field has focused on climate-related financial risks (CRFR), the topic of biodiversity-related financial risks (BRFR) is now gaining momentum very rapidly in many political and economic spheres (e.g. WEF (2021); G7 (2021); OECD (2019); WWF (2021); Chandellier and Malacain (2021); TNFD (2021); Dasgupta (2021)).

Just like CRFR, BRFR can be best characterized through the concept of deep or radical uncertainty rather than probabilistic risk (Kedward et al., 2020). Indeed, regarding physical sources of risks, environmental changes are subject to non-linearities, and tipping points could be reached and cause cascading consequences which are impossible to foresee. On the transition risk side, the rapid "transformative changes" (IPBES, 2019) that must occur to bend the curve of biodiversity loss (Mace et al., 2018) before 2030 and reach biodiversity gains afterwards have never been experienced in such a short time frame and on such a large geographical scale. Therefore, the economic and financial outcomes that could result from current biodiversity-related trends - or attempts to reverse such trends - do not easily lend themselves to probability measurements (Knight, 1921).

In this context, assessing the economic and financial "risks" related to biodiversity, in the sense of the propensity for economic and financial agents to be negatively affected in the future due to such transformations, requires forward-looking scenario analyses,[6] just like in the case of CRFR (NGFS, 2020). Scenario analysis seeks to put forward plausible hypotheses for the future that do not need to - indeed, cannot - be informed by backward-looking economic and financial data. For financial supervision purposes, scenario analysis can be used to assess

[2] For the sake of simplicity, we call "physical risks" the BRFR induced by physical sources of risks, and "transition risks" those induced by transition sources of risks.

[3] IPBES (2019) identified five main direct drivers of biodiversity loss: land and sea use change, direct exploitation of organisms, climate change, pollution, and invasive species. However, each can be decomposed into several dimensions - e.g., land-use change includes, among other, deforestation and urbanization.

[4] Note that along this paper, the term "impacts" will always refer to *negative* impacts on biodiversity.

[5] "Pristine" is understood here as equivalent to a state that is intact and undisturbed by human activity.

[6] One could follow other approaches, such as a precautionary financial policy framework (Chenet et al., 2021). While the latter may be relevant from a policymaking perspective (see Svartzman et al. (2021a) for a discussion), we do not follow it here since the goal of this paper is to understand how far we can go in the exploration of BRFR.

the vulnerability of specific institutions and the financial system as a whole to specific shocks. This has been the case for example in the stress tests conducted by regulatory authorities after the 2008 financial crisis to assess the resilience of banking institutions in adverse macro-financial scenarios (Borio et al., 2014).

More precisely, in order to conduct a forward-looking assessment of nature-related risks, three components are needed (see Fig. 1): (i) a scenario of the hazards or shocks that could translate into economic and financial risks; (ii) metrics of exposure of financial institutions to these hazards/shocks via the firms in their portfolios; and (iii) tools to determine the vulnerability of financial institutions and the firms in their portfolio, i.e., their sensitivity and adaptive capacity given the shock and exposure they face. Regarding step (i), comprehensive biodiversity-related scenarios still need to be designed for the specific needs of central banks and financial supervisors - unlike for CRFR, with the recent development of climate-related scenarios (NGFS, 2020). In the case of physical sources of risks associated with biodiversity loss, existing scenarios mostly depict the disappearance or degradation of a few specific ecosystem services, such as pollination (Kok et al., 2020; van Toor et al., 2020) or the provision of fish and wood (Johnson et al., 2021). On the transition side, some scenarios have been picturing the implementation of new regulations in favour of biodiversity, such as the extension of protected areas (Johnson et al., 2021; Calice et al., 2021) or the reduction of nitrogen in agriculture (van Toor et al., 2020). However, most of them do not capture all the aspects of a "biodiversity transition" (see Maurin et al. (2022) for a detailed and critical presentation of existing global biodiversity scenarios).

Given the lack of commonly agreed biodiversity-related scenarios, this paper proceeds by considering that the static assessments of dependencies to ecosystem services and impacts on biodiversity are appropriate first steps to assess the exposure of economic agents to physical and transition risks (step (ii) of Fig. 1). For physical risks, we assume that a business that is highly dependent on ecosystem services is more likely to be directly affected in case of a physical shock, and hence has a greater a priori exposure to physical risks. Accordingly, we use the dependencies of the economic activities financed by French financial institutions on a range of ecosystem services as a proxy for physical risks. For transition risks, we assume that a business with a significant impact on biodiversity has a higher chance of being affected by a biodiversity transition shock than a business with a low impact. Hence, we approximate transition risks through the negative impacts that the firms financed by French financial institutions have on biodiversity. Our scenario of shock (step (i)) is therefore only implicit – with the idea that physical shocks will affect the firms with higher dependencies on ecosystem services, and transition shocks the firms with more impacts on biodiversity.

In contrast to conventional stress-testing and traditional financial stability assessments, our analysis does not include financial adjustment models aiming to compute the reactions of firms and financial institutions (step (iii)). Indeed, further analysis could explore the consequences of biodiversity-related shocks on assets devaluation or probability of default, as is done for example in Allen et al. (2020) for climate shocks. Further impacts on the financial system through contagion or second round effects, à la Battiston et al. (2017), should also be analysed.

Due to the complexity of biodiversity-related challenges, this paper focuses on quantifying exposure to biodiversity-related shocks. This approach aligns with existing case studies from the Netherlands (van Toor et al., 2020), Brazil (Calice et al., 2021), and Malaysia (World Bank and Bank Negara Malaysia (BNM), 2022), albeit with some nuances. First, we deepen the analysis of firms' dependencies on ecosystem services by including the indirect dependencies coming from the supply chain. Second, we systematically establish a distinction between what we could call "biophysical metrics" applying to the financial portfolio (dependency scores, biodiversity footprint), and "financial metrics" indicating the percentage of the portfolio exposed to firms deemed more likely to be exposed to biodiversity-related shocks. Finally, our paper develops further the conceptual analysis around the notion of "biodiversity-related financial risks" than is done in the case studies mentioned above.

3. Data and method

The data on the securities held by French financial institutions (FFIs) come from the Securities Holding Statistics Sectoral (SHS-S) database (see Boermans (2022)). We restrict our sample to three types of securities (listed shares, short-term debt securities, and long-term debt securities) issued by French and foreign non-financial corporations and held by French financial institutions[7] at the end of 2019. We are then able to find information (turnover, enterprise value, etc., with the C4F database, see below) on only a subset of issuers: eventually, we are able to cover EUR 995 trillion of securities issued by 1126 firms. This sample is hereafter called the "portfolio" of French financial institutions.

We estimate that this portfolio covers 26% of all the listed shares and securities held as assets by French financial institutions - mostly because many of the securities they hold come from government and financial issuers rather than non-financial firms. Of course, French financial institutions also have other assets on their balance sheet than debt securities and listed shares: we estimate that our portfolio is covering approximately 6% of the total asset side of their balance sheet. The assets of commercial banks are less well covered than those of other types of financial institutions, as a large part of their assets are made of loans (loans represented 37% of French banks' assets in 2021, against 9% for debt securities an listed shares).[8] More details can be found in Annex.

3.1. Dependencies and impacts/footprints

3.1.1. Dependencies and impacts at the sectorial and geographical level

The sectorial and geographical classification used in this paper is that of EXIOBASE version 3 (Stadler et al., 2018). EXIOBASE is an open-access, environmentally extended multi-regional input-output table (EE-MRIO) with 163 sectors[9] and 49 world regions (including countries and broader regions). It provides information on the value of output produced by each sector in each region, on the value of intermediary goods used to produce this output, and hence on the value chains of each production sector in each region. We use EXIOBASE in particular to compute the indirect dependency score and impacts on biodiversity stemming from the supply chain. In this paper, we call "direct" the dependency scores or impacts related to the direct operations of the firms - corresponding to the "Scope 1" of the Greenhouse Gas Protocol framework (Otte and Prasad, 2008). We call "indirect upstream" the dependencies and impacts of the suppliers of the firm - upstream "Scope 2" and "Scope 3" of the GHG Protocol. In this paper, we do not assess the downstream footprints or dependencies of firms.

3.1.1.1. Dependency scores. We define dependency scores as a metric illustrating the degree to which a given production process relies upon a specific ecosystem service. A low score indicates no reliance, while a high score signifies that the ecosystem service is hardly replaceable or

[7] More precisely, our data exhaustively covers the securities held by all French financial institutions belonging to the following institutional sectors: deposit-taking corporations except central banks (investor sector S122), money market funds (MMF, S123), non-MMF investment funds (S124), other financial corporations excluding financial vehicle corporations (S125W), and insurance corporations (S128).

[8] This paper focuses on securities due to data constraint, but further extensions could consider exploring the exposure of loans and non-listed shares in particular, to allow for a better coverage of FIs' balance sheets - for banks in particular.

[9] We list the sectors in Table A2.

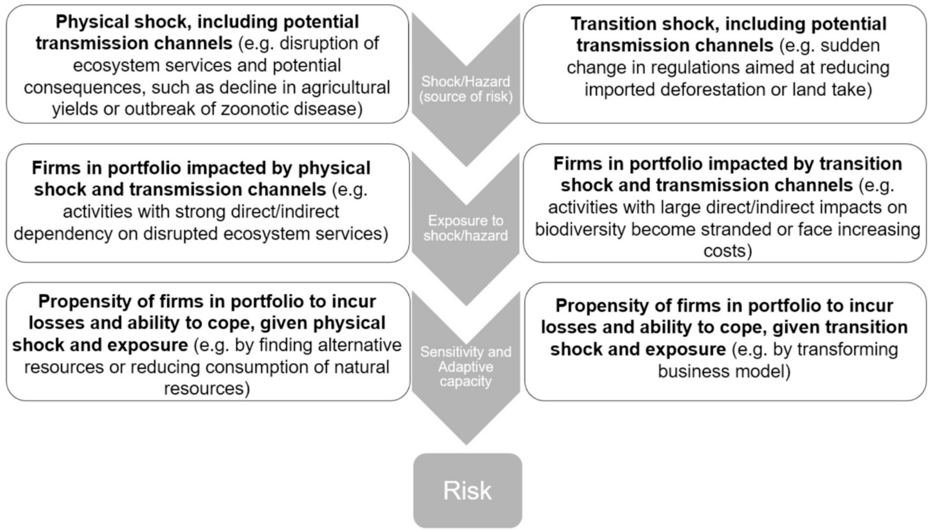


Fig. 1. The three steps needed to conduct a biodiversity-related financial risk assessment.
Source: Authors.

not substitutable for the functioning of the economic activity. We compute the direct dependency score for each EXIOBASE sector by connecting the latter with the ENCORE (Exploring Natural Capital Opportunities, Risks, and Exposure) database, developed by the Natural Capital Finance Alliance and UNEP-WCMC (see Natural Capital Finance Alliance (2021)). It describes the dependency of 86 types of production processes on 21 ecosystem services. The latter are classified according to the Common International Classification of Ecosystem Services (CICES) (see Table A1): 17 of the ecosystem services considered are regulation ecosystem services; the remaining four consist of provisioning services. ENCORE does not include cultural ecosystem services, like those related to recreational activities, nor other relationships linked to intangible forms of attachment to ecosystems or biodiversity, like the spiritual values attached to nature.

To quantify the level of direct dependency of each production process on ecosystem services, ENCORE assigns one among five dependency levels: very low, low, medium, high, and very high.[10] The construction of the levels of dependency of each production process ensues from the degree of disruption to the production process if the ecosystem service were to disappear. In ENCORE, the levels of dependency are not location-specific: for each ecosystem service, a production process in one region is considered to have the same level of dependency as the same production process in another region.

We assign 21 dependency scores to each economic sector (one score per ecosystem service) by connecting the 86 ENCORE production processes to the 163 EXIOBASE sectors. To aggregate the levels of dependency when a sector uses multiple production processes, we convert the five qualitative scores into quantitative scores as follows: no dependency is 0%; very low, 20%; low, 40%; medium, 60%, high, 80%; very high, 100%. Then, we define the sector's score as the simple mean of those scores of the production processes used in the sector. In our interpretation of the results, we will use the terms very low, low, medium, high and very high dependencies to characterize sectors with scores in the intervals 0–20%, 20–40%, 40–60%, 60–80% and 80–100%, respectively. In addition to these direct dependency scores, we compute indirect upstream dependency scores. We do so by using the MRIO table and assigning to a given sector *i* the average of the dependency score of all sector *i*'s suppliers weighted by their importance (in value) in the supply chain of sector *i* (see Annex). Note that although the direct dependency scores are not location-specific, the indirect dependency of a sector is, as the mix of sectors indirectly involved in a sector's supply chain changes depending on the sector's location. Therefore, firms working in the same sector but in two different regions will have the same direct dependency score for a given ecosystem service, however, their upstream dependency scores will differ due to the difference in their supply chains.

3.1.1.2. Biodiversity footprint. We obtain the biodiversity impacts of firms with the "Biodiversity Impacts Analytics-GBS" (BIA-GBS) database, developed by CDC Biodiversité and Carbon4 Finance (C4F). It draws on CDC Biodiversité's Global Biodiversity Score® (GBS 1.1.0), based on the GLOBIO model (Alkemade et al., 2009).[11]

The metric used to measure the biodiversity footprint is the MSA.km^2. The Mean Species Abundance (MSA) is the average abundance of originally occurring species relative to their abundance in the undisturbed ecosystem, understood here as equivalent to a theoretical and a-historical pristine state that is intact and undisturbed by human activity. A loss of 1 MSA.km^2 can be compared to the conversion of 1km^2 of an undisturbed ecosystem - MSA of 100% - into a completely "man-made" area such as a car park - MSA of 0%.[12] The BIA-GBS database splits the biodiversity footprint into a static and a dynamic term. The static part of the footprint includes all the "persistent effects" on biodiversity (i.e., a stock of impacts) caused by those past activities that were needed to enable the current activities of the firm, such as the construction of buildings or parking lots. Conversely, the dynamic part of the footprint includes the changes (or flows) in biodiversity, such as the new

[10] For instance, the functioning of the production process "large-scale irrigated arable crops" depends on the service "water flow maintenance" with a "high" dependency level.

[11] While ENCORE was initially developed for dependencies, one can now also use it to explore impacts. However, it only provides a "materiality" of the impact per economic sector (from very high to very low), but no quantified impact metric. This makes the establishment of the indirect impacts much harder and less precise than with the GBS. In addition, unlike in the GBS, the impacts in ENCORE aren't differentiated by region.

[12] The MSA.km^2 does not provide information on the distribution of impacts. Indeed, an MSA.km^2 of 1 can mean that 1km^2 of intact nature was completely destroyed, i.e., it has an MSA of 0%, hence the impact is 100% on a 1km^2 surface, yielding an MSA.km^2 of 100% $\times$ 1 = 1. However, it can also mean that 10km^2 were only partially impacted by human activities and reached an MSA of 90% - hence the impact is 10% on each 1km^2 surface, yielding an MSA.km^2 of 10% $\times$ 10 = 1. Therefore, the interpretation of MSA.km^2 that we propose here simplifies the reality of impacts.

biodiversity consumption, restoration, or conservation, due to the firm's activities *during the assessment period* (e.g., one year). We chose to base this paper's analysis on the static footprint only (but the dynamic footprint assessement can be found in Svartzman et al. (2021b)). Indeed, it makes the results more straightforward, and the dynamic footprint computed by BIA-GBS relies on heterogeneous data sources that would have made the results more challenging to interpret.

The GBS conducts the biodiversity footprint assessment for each sector-region pair in two main steps (building on Wilting and van Oorschot (2017)). First, it assesses the contribution of economic activities to pressures on biodiversity - also called drivers of biodiversity loss. It employs EXIOBASE to convert data on the turnover by sector and region into material inputs used for production (commodities, products, and water) and emissions of pollutants. Material inputs and pollutants are then translated into various pressures on terrestrial and aquatic freshwater biodiversity.[13] In this paper, we focus on impacts on terrestrial biodiversity - because impacts on terrestrial and aquatic biodiversity cannot be easily aggregated - and on the static impacts that do not include the climate change pressure on biodiversity.[14] Second, the GBS converts these pressures into impacts on biodiversity, expressed in MSA.km^2, using the impact factors provided by the GLOBIO model (Alkemade et al., 2009) developed by the Dutch environmental agency (PBL). Note that it computes both the direct and indirect upstream impacts of sectors' production (using a classic Leontief inverse matrix obtained with the EXIOBASE).

3.1.2. Dependencies and impacts of firms

We use the regional and sectorial dependency scores and footprints to obtain the dependency scores and footprints of the non-financial firms that issued the securities owned as assets in the portfolio of French financial institutions. Based on the ISIN codes of the assets, we first link the securities to the firms that issued them using an in-house C4F referential database. Then, for each firm in the portfolio, we compute dependency scores and a biodiversity footprint based on the sectors and regions where it operates. We obtain the dependency scores of the firm by taking the average dependency score of the firm's sector-region pairs weighted by the share of the firm's turnover that originates from the given sector-region. We obtain the biodiversity footprint of the firm by summing its sector-region footprints, which depend on the turnover value originating from the sector-region. The turnover breakdown of firms by sector and region comes from the proprietary CRIS database developed by C4F using external financial and corporate data and internal expertise.

3.1.3. Dependencies and impacts assigned to the portfolio

We compute the portfolio's dependency score for a given ecosystem service by weighting the dependency scores of the different firms in the portfolio by the share they represent in the value of the portfolio. We obtain 21 dependency scores for the portfolio, one for each of the 21 ecosystem services.

On the impact side, we assign only a share of the biodiversity footprint of firms in the portfolio to the portfolio itself. This share corresponds to the importance of the portfolio's assets in the enterprise value[15] of the firms,[16] obtained from the company's annual report or from an external financial data provider. Note that our allocation rule differs from that of van Toor et al. (2020), who use the market capitalization of firms – rather than the enterprise value – to assign a share of the biodiversity footprint to the portfolio. We prefer to use the enterprise value because this allows us to account for the footprint of non-listed firms. In addition, from a theoretical perspective, we consider that it makes sense to attribute the biodiversity footprint of a firm to all the holders of the securities issued by the firm rather than to its shareholders only.[17]

3.2. Portfolio exposure to high-stake firms

In order to go beyond the biophysical assessment of the portfolio's dependencies/impacts and to move closer to a monetary assessment of the exposure to risk, we assess the portfolio's exposure, in euros, to "high-stake" firms. When a firm is deemed "high-stake," we consider the total value of the security it issued exposed. We define high-stake firms as the firms most likely to face physical or transition risks because they exceed a certain threshold regarding dependency scores or biodiversity footprint. We set absolute thresholds in the case of physical risks and relative thresholds in the case of transition risks. Indeed, whether a firm is subject to a physical shock does not depend on whether the other firms have a high dependency score. However, the exposure to transition risk may depend on the footprint of other sectors, as policymakers intending to protect biodiversity may first regulate the firms with the most significant impacts.

3.2.1. Physically high-stake firms

For physical risks, we define "high-stake" companies or sectors as companies and sectors that have some high dependency scores, or several moderate dependency scores. More precisely, we focus on those with at least one "high" (>60%) or "very high" (>80%) direct dependency score, and second, we look at those with at least five "moderate" (>40%) direct dependency scores. Indeed, even firms with a medium dependency on a wide range of ecosystem services can be "high-stake." If the same underlying ecosystem provides ecosystem services, the degradation of the ecosystem may result in the simultaneous degradation of several ecosystem services.

3.2.2. Transition high-stake firms

Concerning transition risks, we define "high-stake firms" as those operating in "high-stake sectors." Indeed, we cannot define a relative threshold based directly on the biodiversity footprint at the firms level, as we would need to know the footprint of all existing firms while we only know those of the firms in the portfolio. Conversely, defining high-stake sectors is possible as we can set the relative thresholds on an

[13] Some of the pressures are directly obtained from EXIOBASE, while others require the use of in-house tools developed by CDC Biodiversité. The GBS partly covers the drivers of biodiversity loss defined by IPBES (2019), but some have yet to be included, like invasive species, unsustainable hunting and fishing, some sources of pollution like plastic, or pressures on marine biodiversity more generally. Climate change is included in the dynamic footprint but not in the static one, on which this paper focuses.

[14] Climate change is included in the dynamic footprint of the GBS, but not in the static one used in this paper. However, as GHG emissions cumulated over 1750–2018 were approximately 50 times higher than the annual GHG emissions of 2019, CDC Biodiversité (2023) estimates that the static impact on biodiversity due to climate change is approximately equal to 50 times the dynamic impact on biodiversity due to climate change. Limitations to this estimation can be found in CDC Biodiversité (2023).

[15] The enterprise value is the sum of the market capitalization of equity shares, the market value of debt, and the minority interests (investment in another company), minus the total cash and cash equivalents.

[16] We could have chosen another allocation of the firms' footprints to the portfolio. For example, we could allocate the entire firm's footprint to the portfolio as soon as one euro is invested in the firm. In this case, the portfolio's footprint would equal the sum of the companies' footprints in the portfolio. The footprint obtained is indeed the result of a choice in the attribution of company footprints to the portfolio itself. Here, we chose to take into account the importance of investors in the financing of companies.

[17] Note that the footprint we compute includes double counting, for example because the direct footprint of a company can be the indirect footprint of another. Although it may be an issue when assessing the "responsibility" of financial institutions in biodiversity degradation, this is not necessarily a problem when taking a risk perspective, in which all types of exposure should be considered.

exhaustive set of agents (all the sectors-regions of the world). This choice is also motivated by the prospect that transition shocks are more likely to appear at the sector level than at the firm level, as for example regulations tend to be sectoral. We define high-stake sectors as those with a relatively large biodiversity footprint, in absolute terms and/or relative to the sector's turnover. Sectors with a large biodiversity footprint seem more prone to be the target of regulations or changes in consumer demand, for example because they are under the spotlight of environmental NGO reports. In addition, it may be more difficult for the sectors with the most negative impacts on biodiversity to adapt to the new norms, as it will require bigger changes in its production processes. More precisely, we set as "transition high-stake" the sectors whose median biodiversity footprint (absolute or relative to the sector's turnover) across regions is in the top 10% of sectors' median biodiversity footprints worldwide. As this threshold is quite arbitrary, we provide a sensitivity analysis in Annex. The high-stake sectors we obtain (see Section 4) are consistent with the sectors at stake in various biodiversity strategies and transition plans, like the EU Biodiversity strategy for 2030 (European Commission, 2020) or the Global biodiversity outlook (Secretariat of the Convention on Biological Diversity, 2020).[18] Finally, we define two options to decide whether a firm operating in a high-stake sector is itself high-stake. In option *a*, a firm making >50% of its turnover in high-stake sectors will be considered high-stake. In option *b*, a firm making >1€ of its turnover in high-stake sectors will be considered high-stake. These options enable us to test the sensitivity of our results to the allocation rule, as fewer firms will be considered high-stake in option *a* than in option *b*. We provide sensitivity analyses to those parameters in Fig. A4.

4. Results

4.1. Exposure to physical sources of risk

In this section, we first evaluate the physical dependency of the portfolio as a whole by describing its dependency scores. Second, to identify parts of the portfolio that are potentially at risk, we focus on the value in the portfolio that is exposed to "physically high-stakes" companies.

4.1.1. Dependency scores of the portfolio

We find that the direct dependency scores of the portfolio differ greatly depending on the ecosystem service considered (Fig. 2). The most significant dependency scores are found for surface water and groundwater (40–50%). This is because security issuers in the portfolio belong to a large extent to secondary sectors (e.g., manufacturing), many of which rely on production processes depending on water in ENCORE.

We obtain null direct dependency scores for pollination, animal-based energy, maintaining of nursery habitats, and disease control. Indeed, primary sectors such as agriculture, which rely heavily on these ecosystem services, represent a small share of GDP in France and, therefore, of financial institutions' balance sheets. Moreover, agricultural activities are often financed by bank loans, which are excluded from the scope of our study. These results show that if we are to account for physical BRFR, we cannot rely entirely on direct dependencies (e.g., disruptions in agriculture could have important impacts through value chains).

Some of the limitations of a direct dependencies approach are partially overcome when looking at upstream dependencies (Fig. 2): the portfolio is at least slightly dependent on all ecosystem services (all scores become non-null). For example, the portfolio becomes slightly dependent on pollination because the agri-food sectors purchase intermediate commodities from the agriculture sector and issue securities held by French financial institutions. The upstream dependencies of the portfolio on mass stabilization and erosion control, flood and storm protection, and climate regulation are higher than direct dependencies. This suggests that the suppliers of companies issuing the portfolio securities are more exposed to the degradation of these ecosystem services. However, one might have expected upstream dependency scores to be systematically higher than direct ones, as the dependencies of suppliers on ecosystem services are likely to be higher when we get closer to primary sectors. We do not find such a result because our methodology computes upstream dependency scores as weighted averages of dependency scores of sectors in the supply chain. Therefore, a high dependency score for one sector in the supply chain might be lessened by low dependency scores for other sectors.

4.1.2. Portfolio value exposed to "physically high-stake" firms

We identify the value of the portfolio most exposed to physical risks by looking at the securities issued by "physically high-stake" firms. A significant part of the portfolio value could be affected by the disruption of specific ecosystem services (Fig. 3). We find that 21% of the portfolio value comes from firms that are at least moderately dependent on five or more services (cf. first bar). In addition, 42% of the portfolio value is made of securities issued by firms that are at least highly dependent on at least one ecosystem service (dependency score > 60%, second bar), and 9% are very highly dependent on at least one ecosystem service (dependency score > 80%, third bar).

The very high direct dependency scores are concentrated on two ecosystem services: surface water and groundwater (left-hand side of Fig. 4). This suggests that if the quantity and quality of these ecosystem services were to decrease, the situation would likely result in substantial disruption of production processes relying upon them and potentially high exposure and vulnerability of the portfolio to the shock. This high dependency on water is consistent with other studies, notably Delannoy (2016), which concluded that water was the ecosystem service "used" by the most significant number of French economic sectors. Looking at upstream dependency scores (right-hand side of Fig. 4), we find that all securities in the portfolio are issued by firms that are at least slightly dependent on all ecosystem services through their supply chains.

To explain these results, we can look at the dependencies of the sectors to which firms in the portfolio belong. Fig. 5[19] shows that the portfolio is particularly exposed to chemicals production (CHEM), post and telecommunications (PTEL), manufacture of medical, precision and optical instruments, watches and clocks (MEIN), real estate activities (REAL), other service activities (OSER) and manufacture of beverages (BEVR). The heatmaps illustrate each sector's direct and upstream dependency scores on each ecosystem service. Looking at direct dependencies (Fig. 5), we see that among these sectors, only the manufacture of beverages (BEVR) has a very high dependency score on two ecosystem services: surface water and groundwater. All sectors are at least moderately dependent on these two ecosystem services, in particular the agricultural sectors (OTCR, the cultivation of crops, and OMEA, the breeding of animals for meat, very highly dependent), the

[18] An important limitation of the approach is that the discrimination of high-stake sectors should ideally be specific to each region. If it were, this would capture that a sector closer to best environmental practices than similar sectors in other countries is likely to be less exposed to transition shocks.

[19] We build the top histogram as follows: when FFIs hold x€ of securities in company c, and if the company operates in various sectors, we allocate to sector s the amount invested in proportion to the turnover of company c that comes from sector s. Therefore, the sum of all the bars equals the total portfolio value (there is no double counting). The correspondence table between sector codes and names is in Annex. Regarding the heatmap for upstream dependency scores: there are, in fact, numerous upstream dependency scores for each sector, as the upstream dependency score also depends on the region where production takes place. As French issuers are the most represented in the portfolio, this map represents the upstream scores for French sectors.

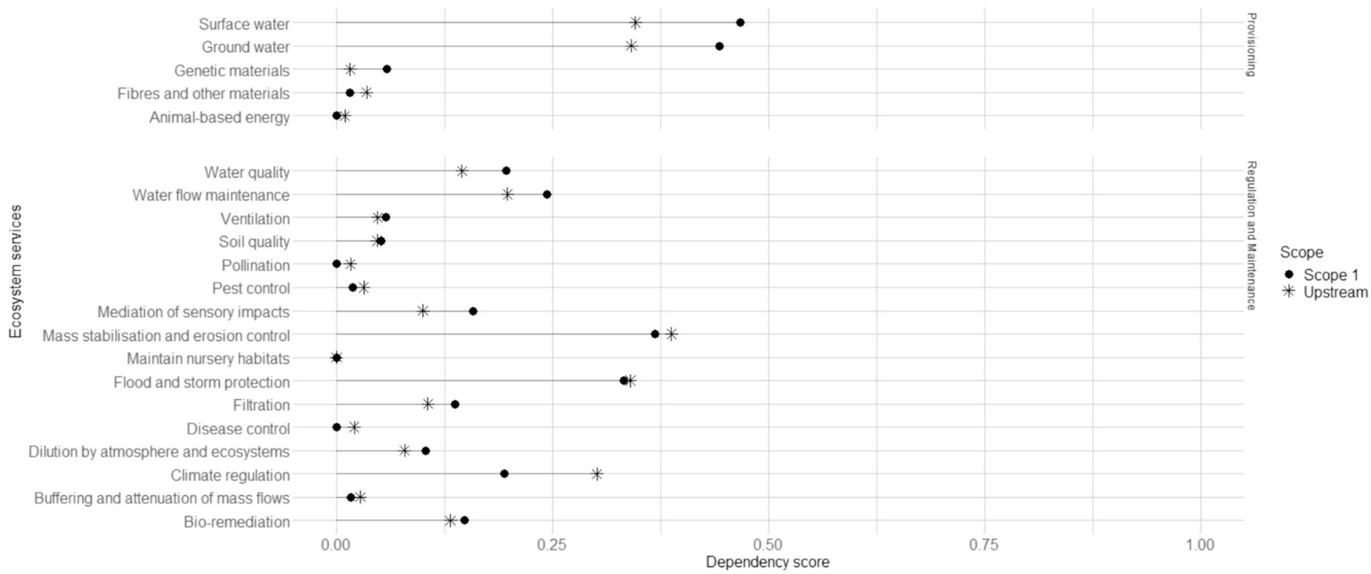


Fig. 2. Direct and indirect upstream dependency scores of the security portfolio.
Source: Authors.

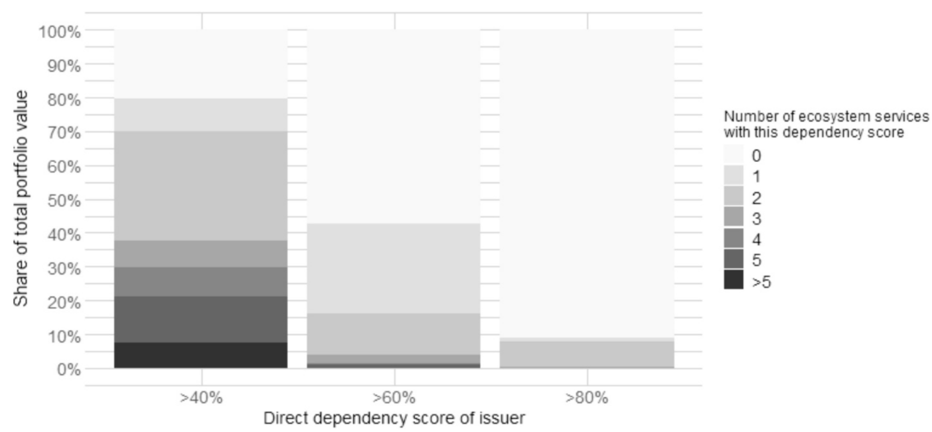


Fig. 3. Share of the portfolio issued by firms directly dependent on *n* ecosystem services at least moderately, at least highly, and at least very highly.
Source: Authors.
Lecture note: The bottom of the first bar indicates that around 8% of the market value of securities in the portfolio of FFIs were issued by companies that are at least moderately dependent (dependency score > 40%) on more than five ecosystem services.

sectors related to mining and quarrying (from IRON to CHMF, highly dependent) and the sectors related to food processing (from PPLT to BEVR, very highly dependent). Overall, the sectors with the most numerous and higher dependencies appear to be the agricultural sectors, the food processing sectors, the collection, purification and distribution of water (WATR), and wastewater treatment (WASO). French financial institutions, however, have relatively low exposure to these sectors. Finally, we find that paying attention to upstream dependencies is important, in particular for sectors related to food processing (from PPLT to BEVR), whose supply chain appears to be on average at least slightly dependent on *all* ecosystem services, due to their reliance on agricultural inputs.

4.2. *Exposure to transition sources of risk*

This section aims to identify the biodiversity-related transition risks for the security portfolio of French financial institutions. We first assess the biodiversity footprint of the whole security portfolio. Then, we evaluate the share of the portfolio value that is exposed to "transition high-stake" companies and sectors.

4.2.1. *Biodiversity footprint of the portfolio*

We find that the static terrestrial biodiversity footprint attributed to the security portfolio of French financial institutions is 130,000 MSA.km^2, comparable to the conversion of 130,000km^2 of natural ecosystems into a completely artificial area.[20] As an order of magnitude, this corresponds to 24% of the area of metropolitan France. On average, one million euros of securities from the portfolio of French financial institutions have a static footprint of 0.13 MSA.km^2, comparable to the complete loss of 0.13km^2 of pristine nature (approximately 16 football pitches). Overall, these results are consistent with those obtained for the portfolio of Dutch financial institutions. Indeed, the Dutch central bank (DNB) (van Toor et al., 2020) finds a biodiversity footprint of 58,000 MSA.km^2.yr and a corresponding average biodiversity "intensity" of

[20] Remember that this static footprint doesn't account for the climate impacts of the portfolio on biodiversity. Those can be roughly estimated to 200,000 MSA.km^2, based on Svartzman et al. (2021b) - providing the climate dynamic impact of the portfolio on biodiversity - and CDC Biodiversité (2023). See footnote 13 for more detail.

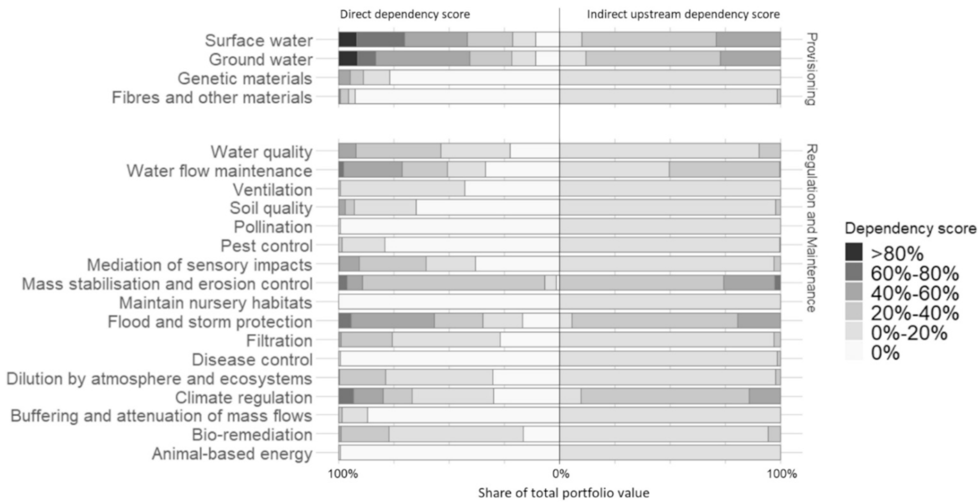


Fig. 4. Distribution of direct (left) and indirect upstream (right) dependency scores in the portfolio.
Source: Authors.
Lecture note: The black portion at the top of the left column indicates that about 5% of the market value of securities in the portfolio of FFIs were issued by companies that are very highly dependent (dependency score > 80%) on surface water.

0.18 MSA.km^2.yr per million euros in the portfolio.[21]

The main drivers of the static footprint attributed to the portfolio are land use and land-use-related drivers of biodiversity loss, particularly the encroachment and fragmentation of habitats (Fig. 6). A large share of this footprint is due to the activities of the suppliers of the firms in the portfolio (what we call "indirect upstream") rather than from the activities of the firms themselves ("direct", or "scope 1" in Fig. 6). In particular, direct suppliers ("Tier 1 of indirect upstream") explain 42% of the total footprint, probably because many securities held by French financial institutions come from firms in secondary sectors. Indeed, firms in those sectors (e.g., food processing) do not necessarily use much land in their production process but rely on inputs that can exert substantial land-use pressures on biodiversity (e.g., crops or cattle). The absence of the "climate change" pressure mentioned above may also explain why the direct impacts are relatively small.[22]

Finally, the static impacts of the portfolio mainly come from a few sectors (Fig. 6). Chemicals production, processing of dairy products, manufacturing and distribution of gas, manufacturing of beverages, and processing of other food products represent more than half of the total static biodiversity footprint of the portfolio. This can be because production in these sectors or in the sectors of their suppliers has substantial static impacts on terrestrial biodiversity. This is the case for food processing sectors (processing of dairy products, manufacturing of beverages, processing of food products). Indeed, the production of one euro of turnover for companies in the portfolio belonging to these sectors has a particularly high static biodiversity footprint. However, this is less the case for sectors like chemicals production, and manufacturing and distribution of gas (see Section 3.2). Instead, their sizeable contribution to the portfolio's footprint comes mainly from the fact that they represent a relatively large portion of the portfolio. Indeed, 11.7% of the securities held by French financial institutions come from the chemicals sector and 3.7% from the manufacturing and distribution of gas sector (Fig. 5).

4.2.2. *Portfolio value exposed to "transition high stake" firms*

We now use the static footprint of firms in the portfolio to determine which firms are "transition high-stake", i.e., more likely to be exposed to transition-related shocks.[23] We then assess the share of the portfolio value exposed to those companies.

Firms with a relatively high biodiversity footprint or biodiversity intensity of turnover, which may be more exposed to transition shocks, issued a small part of the portfolio securities (Fig. A3). However, defining a threshold above which a firm can be deemed "high-stake" is difficult, as explained in Section 3.2.2.

Therefore, to provide intuitions about the type of activities that may be most exposed to a transition shock, we focus on "transition high-stake sectors," whose median biodiversity footprint and/or median biodiversity intensity of turnover is in the top 10% of median footprints or intensities of sectors. The sectors we obtain (Fig. 7 and Table A3) are consistent with those having the most significant impacts on biodiversity according to other analyses. For example, UNEP (2021) uses the ENCORE database and finds that the sectors with more impacts on biodiversity are beef and dairy, distribution, mining, oil and gas exploration, drilling and transportation, airport services and marine ports and services. NABU and BCG (2020) identifies farming, forestry, mining and extractive sectors, industrial production, and infrastructure expansion. In our work, which focuses more on the land-use change driver of biodiversity loss, the "high-stake sectors" found are mostly related to the transitions on land and forest, agriculture, food, and cities and infrastructures listed in the Fifth Global Biodiversity Outlook (Secretariat of the Convention on Biological Diversity, 2020). Such sectors are also central in other political strategies to bend the curve of biodiversity loss, such as the European Biodiversity Strategy for 2030 (European Commission, 2020) which aims to decrease the use of pesticides by 50%, or France's law setting up a "no-net land-take" target for 2050.

[21] Various things may explain the slight differences in our results. We consider different types of securities and issuers, as we look at debt securities and listed shares issued by non-financial firms. In contrast, the DNB considers only the listed shares issued by financial and non-financial firms. Second, the impacts assessed by the DNB are time-integrated (see Wilting and van Oorschot, 2017) while the BIA-GBS methodology that we use distinguishes between the stock ("static" footprint") and flow ("dynamic" footprint) of impacts. Finally, we focus on the static impacts that do not include the impacts of climate change on biodiversity, while they are included in the DNB's results.

[22] For instance, as the direct operations of manufacturing activities tend to be rather carbon-intensive, accounting for the climate change pressure on biodiversity would likely increase the contribution of Scope 1 to the overall footprint.

[23] The "high-stake" firms and sectors obtained would have been different if we had taken the *dynamic* footprint into account, which includes impacts on biodiversity due to climate change.

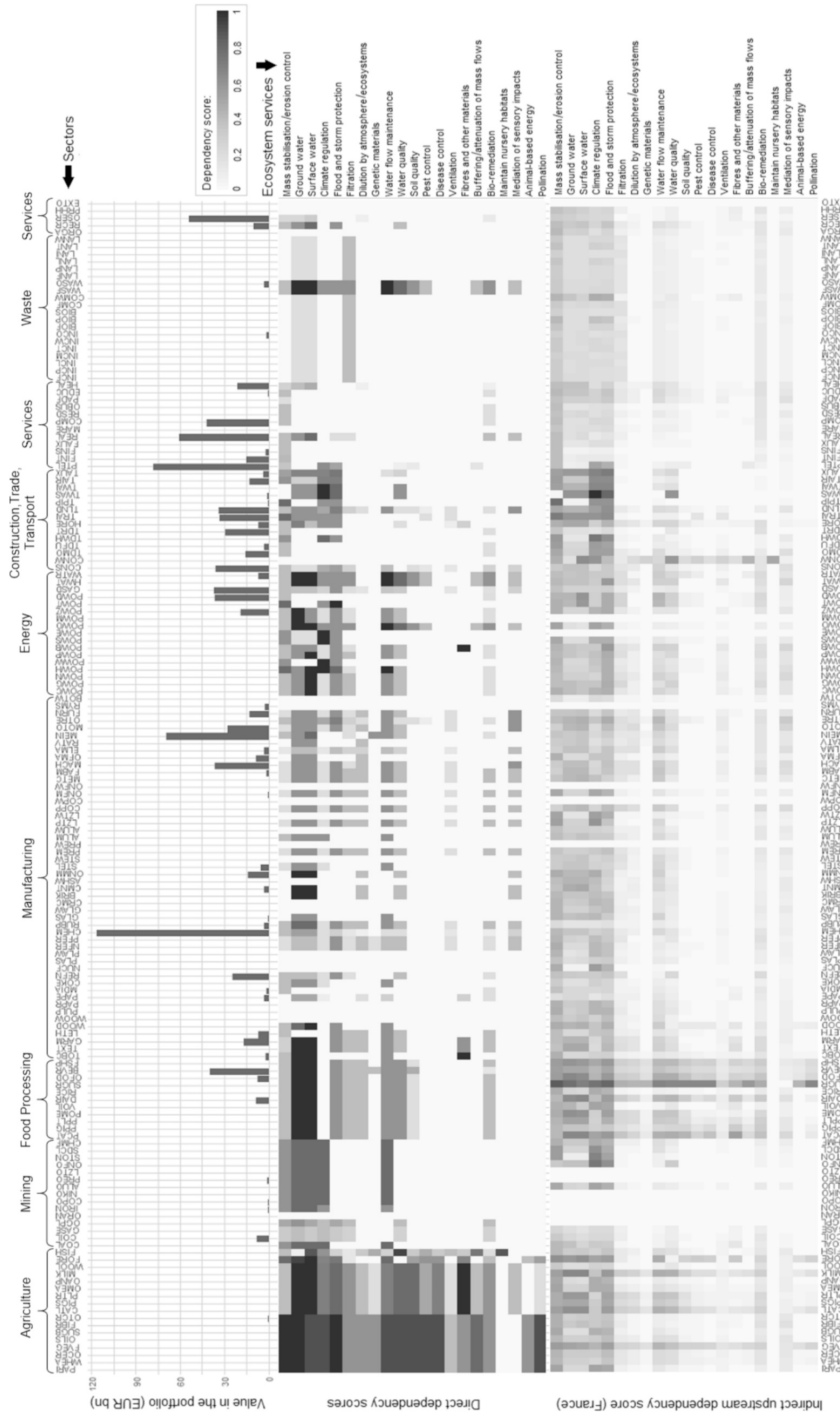


Fig. 5. Securities in the portfolio by sector, and heatmaps of direct and indirect upstream dependencies by sectors and ecosystem services.
Source: Authors.

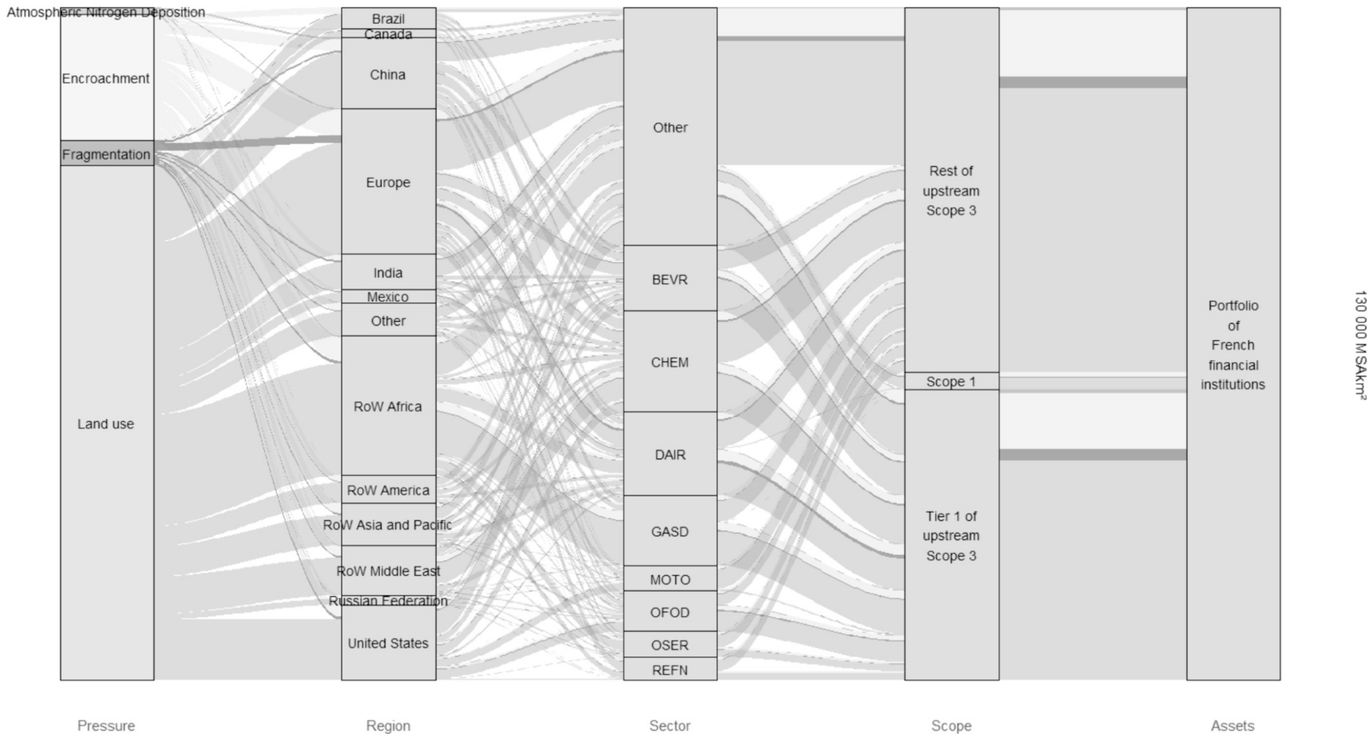


Fig. 6. Decomposition of the portfolios' static biodiversity footprint.
Source: Authors.

Adopting first a restricted definition of high-stake sectors based on having *both* a high (median) footprint and a high (median) biodiversity intensity of turnover relative to other sectors, and considering direct (Scope 1) impacts only, we obtain mostly primary sectors (agriculture, forestry or mining, cf. Table A3). Considering also the indirect impacts from the upstream supply chain introduces some secondary sectors related to the manufacturing of food products (especially meat) or wood products. When extending the definition of "high-stake" to sectors with *either* a high biodiversity footprint *or* a high biodiversity intensity of turnover, and considering direct impacts only, new agricultural or mining sectors appear, such as the cultivation of plant-based fibers or the mining or copper. However, despite this increase in the number of high-stake sectors, those aren't much represented in the portfolio; hence the associated share of the portfolio exposed does not increase very much. Finally, including both direct and indirect upstream impacts captures new sectors with a relatively low biodiversity footprint but a high biodiversity intensity of their turnover, such as construction or hotels and restaurants. This results in the share of the portfolio value exposed to high-stakes sectors increasing to >20% (Table 1). For instance, 38.5% of the portfolio value is issued by companies deriving at least 1€ of their turnover (Option b) from sectors in the top 10% in terms of either high absolute footprint or intensity of turnover.[24]

These results show that the security portfolio of French financial institutions may not be exposed directly to transition shocks, because their securities do not come from firms in the most directly exposed sectors like agriculture or forestry. However, it may be exposed indirectly through a trickling down in the supply chain, e.g., for sectors such as agri-food, hotels and restaurants or construction.

Finally, the analysis conducted in this section clarified the various possible uses of the impact/footprint metric. A focus on the footprint of *security issuers* (firms or sectors) seems appropriate to assess transition risks: this allows to evaluate the share of the portfolio value issued by the firms or sectors that are most likely exposed to transition shocks (Section 4.2.2). The *portfolio* footprint (Section 4.2.1) rather allows identifying a "responsibility" or "contribution" of the portfolio of French financial institutions to impacts on biodiversity through the firms it finances.[25] This distinction clarifies why, for example, article 29 of the French Energy-Climate law (Ministry for the Economy and the Recovery, 2021) mentions the "measurement of impacts on biodiversity" as a way to assess both (i) the transition risks for the portfolio and (ii) whether the portfolio is "aligned" with international targets and contributes to reducing impacts on biodiversity, in a double materiality perspective.

5. Discussion

Our analysis of dependencies and impacts of firms in the portfolio faces methodological limitations. For both, we evaluated average dependencies and impacts at the sector-region levels, preventing the identification of within-sector heterogeneities - for example, between organic and non-organic farms within the agricultural sector. Regarding the dependencies assessment, one limitation is that when a firm operates in multiple sectors, we considered that its dependency score was a weighted average of the sectorial dependency scores. However, to capture the *risks* faced by firms, it could be wiser to define the firm's dependency score as the maximum of the sectorial dependency scores (see section A.2.2). This would better represent the fact that even if only a tiny part of its activity is in a sector highly dependent on ecosystem service *E*, a company may still become unable to operate in case of *E*'s collapse. A similar issue applies to the computation of indirect dependency scores: a physical shock leading to the lack of an essential input could threaten the whole production process, whatever the monetary share of the input in the firm's supply chain.

Regarding the footprint assessment, the data on land use in the GBS

[24] When we look at companies with >50% of their turnover in high-stake sectors (Option a), the portfolio's exposure is still 24.1%.

[25] In this aim, it could be preferable to avoid double counting, e.g., by using a consumption-based rule that allocates footprint to final demand (Wiedmann, 2009), or a shared-responsibility rule (Gallego and Lenzen, 2005).

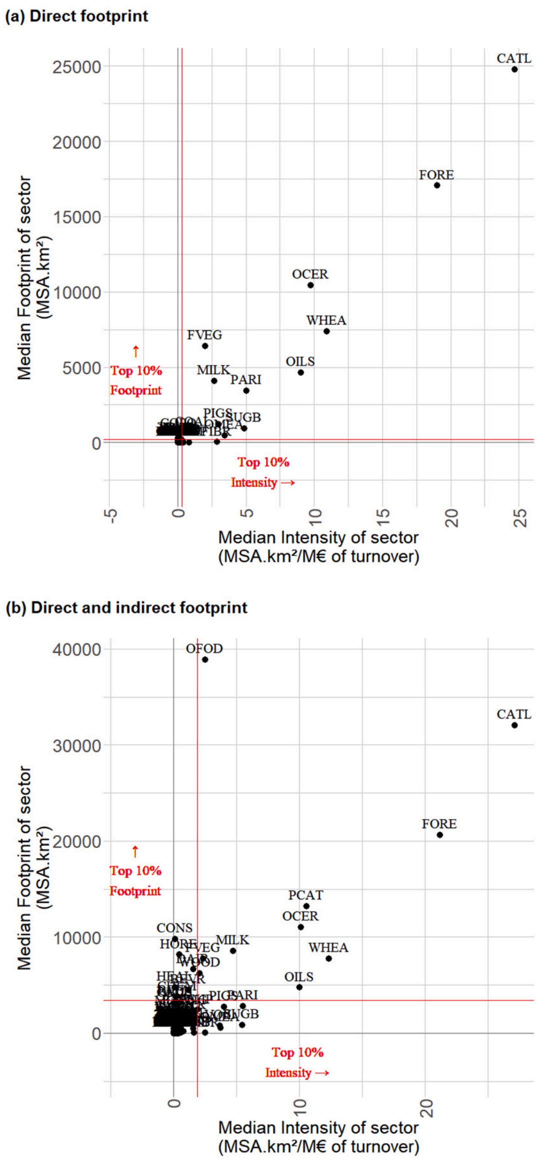
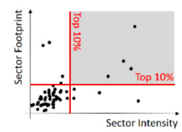
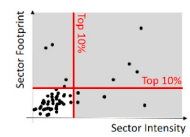


Fig. 7. Sectors in the top 10% in terms of median footprint and median intensity.
Source: Authors.

comes from EXIOBASE, which for example allocates the urban land use to households rather than to productive sectors such as construction, transport, or logistics. This downsizes these sectors' impacts and associated risks - as, for example, those associated with the emerging French 'no net land-take' policy aiming to limit the expansion of urban areas to protect biodiversity and agricultural land. In addition, our footprint analysis focused on impacts on terrestrial biodiversity due to land use. Therefore, it misses some other drivers of biodiversity loss like climate change (although carbon-intensive sectors are already well studied by the literature, see for example the Climate Policy Relevant Sectors in Battiston et al. (2017)) or invasive alien species (which, if included, could put the light on sectors relying on long-distance transportation) and the impacts on aquatic and marine biodiversity.

Table 1
Portfolio value exposed to "transition high-stake" sectors.

		Top 10% in terms of	
		Direct footprint	Direct and indirect footprint
	Top 10% in terms of **both** footprint **and** intensity	12 high-stake sectors Portfolio exposure: – option a: 0% – option b: 0.2%	10 high-stake sectors Portfolio exposure: – option a: 0.9% – option b: 1.5%
	Top 10% in terms of **either** footprint **or** intensity	20 high-stake sectors Portfolio exposure: – option a: 0.1% – option b: 1.2%	22 high-stake sectors Portfolio exposure: – option a: 24.1% – option b: 38.5%

Anyhow, the evaluation of dependencies and impacts is a necessary but insufficient step toward assessing risks per se (Fig. 1).[26] First, one should define more precisely the shocks faced by the economy. Locating degraded ecosystems is crucial to assess the likelihood of ecosystem service degradation and hence of physical shocks[27] (see e.g. Hadji-Lazaro et al. (2023)) but also of transition shocks, as it could indicate the likelihood of a reaction to protect them. Hence, the definition of "high-stakes" activities with respect to biodiversity goes hand in hand with the development of narratives on the evolution of ecosystem services (for physical risk assessments) and norms to protect biodiversity (for transition risk assessments) in order to specify the type, location and time-horizon of shocks. A proper risk analysis should also include information on the adaptive capacities of the agents exposed to shocks. Assessing their financial fragility (liquidity, solvency) is critical to identify whether the shock is large enough to cause payment defaults (in the vein of Godin and Hadji-Lazaro (2022)). In addition, further research should go beyond exposure analysis and explore the broader macroeconomic consequences that could ensue from physical and transition shocks. For example, a decline in pollinators or the establishment of protected areas could affect food supply and prices, with consequences on the distribution of demand between food and non-food consumption, and macrofinancial impacts - on government debt, aggregated demand, unemployment, etc.

Finally, some implications can be drawn from our results, keeping in mind that our message so far is not that financial institutions should seek to divest from all the "high-stake" sectors we identified. Indeed, on the physical risk side, it is impossible to become independent from ecosystem services - especially "public-good" ecosystem services, such as climate regulation or protection against diseases. Attempting to reduce one's dependencies on ecosystems may even deteriorate ecosystems further (e.g., shifting away textile production from plant-based fibers to synthetic ones may lead to increased plastic pollution), eventually increasing systemic risks. Instead, the focus should be on limiting

[26] This is also the intuition of the TNFD framework. The latter calls for a risk assessment with an "evaluate" phase - corresponding to the exposure assessment performed in our paper - complemented with a "locate" and an "assess" phase aiming respectively to characterize the shocks that could occur and the adaptive capacities of exposed agents.

[27] This requires linking the (observed or forecasted) health of ecosystems to their ability to provide ecosystem services, although non-linearities can make it difficult. For this purpose, one could use approaches such as the one of the IUCN Red list (Keith et al., 2013), the ESGAP framework (Usubiaga-Liaño and Ekins, 2022) or water-scarcity projections.

the probability of physical shocks by limiting the negative impacts on ecosystems - this relates to the endogeneity of risk and the debates around "double materiality," explored by Boissinot et al. (2022). On the transition risk side, further work is needed to distinguish, within each sector, between the production processes with negative impacts and less negative ones. This calls for a more qualitative analysis of sunset and sunrise business models related to biodiversity, in the vein of the European green taxonomy (Schrems and Bär, 2021). Exploring the details of the "transition shocks" at stake and the activities most exposed to them will pave the way for prudential regulations related to biodiversity loss - in the spirit of some climate-related prudential regulations that have been proposed and implemented (Rozenberg et al., 2013; Campiglio, 2016; D'Orazio, 2022).

6. Conclusion

This paper has explored biodiversity-related financial risks (BRFR) for the French financial system. First, we provide quantitative estimates of the dependencies on ecosystem services and the impacts on biodiversity of the security portfolio held by French financial institutions in 2019. We find the highest portfolio dependency scores for ecosystem services related to the provision of surface water and groundwater provision, the protection against floods and storms, and climate regulation – highlighting the overlap between biodiversity and climate sources of risks. Accounting for the dependency on ecosystem services in the value chain of firms is important and increases the dependency score of the portfolio to certain ecosystem services, like pollination or erosion control. Regarding the impacts on biodiversity, we find that the static terrestrial biodiversity footprint of the securities held by French financial institutions is comparable to the loss of at least 130,000km^2 of pristine nature. This footprint focuses mostly on land-use related impacts and is therefore a conservative estimate. Second, we identify firms that are more prone to be impacted by biodiversity-related shocks, so-called "high-stake" firms, based on their dependencies (for physical risk) and impacts (for transition risks). This enables us to compute a share of the portfolio value exposed to such firms. On the physical risks side, we find that firms that may be more exposed to physical shocks operate in the agriculture, mining, or food processing sectors. Around 40% of the portfolio value held by French financial institutions is exposed to firms highly or very highly dependent on at least one ecosystem service. On the transition risks side, we obtain that the most "high-stake" firms operate in sectors such as agriculture, forestry, and mining, which have large direct impacts on terrestrial biodiversity. They also operate in the food processing, chemicals, or construction sectors, which have significant indirect impacts on terrestrial biodiversity through their supply chains. Hence, while the firms in the portfolio of French financial institutions may not be very exposed to transition shocks directly, around 30% of the portfolio value could be exposed to transition high-stake firms when we account for the impacts of their supply chain on biodiversity. Finally, these results could feed into further financial risk assessments. This would require detailing the nature of the physical and transition shocks, including potential transmission channels across sectors and the adaptive capacity of economic and financial agents. Overall, this paper contributes to further uncovering the linkages between biodiversity loss and financial instability while emphasizing the numerous associated caveats and sources of uncertainty.

CRediT authorship contribution statement

Paul Hadji-Lazaro: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing, Investigation, Supervision. **Mathilde Salin:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing, Supervision. **Romain Svartzman:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **Etienne Espagne:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **Julien Gauthey:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **Joshua Berger:** Conceptualization, Data curation, Methodology, Resources, Validation, Writing – review & editing. **Julien Calas:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – review & editing. **Antoine Vallier:** Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – review & editing.

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 data that has been used is confidential.

Appendix A. Annex

A.1. Annex 1: Financial data

A.1.1. Construction of the "portofolio" sample

The SHS data: The Securities Holding Statistics - Sectoral (SHS-S) are compiled by the European System of Central Banks (ESCB). They comprise "security-by-security holdings and transactions aggregated at the level of investor sector for each investor country, comprising a full economy view of financial and non-financial investors" and "benefit from very high coverage across euro area investors, relying on harmonized reporting and data preparation by the ECB since 2013-Q4" (Boermans, 2022).

Initial filters: Starting from the SHS-S dataset, we focus on the (positive) positions in terms of listed shares and debt securities (shares/units were removed) held in 2019Q4. This yields a sample of EUR 4.90 trillion: 79% of this value is held by French financial institutions (investor sector S12) - the rest by is held by non-financial institutions (13%), other households and non-profit institutions serving households (5%), and the government (3%)). Among the listed shares and debt securities held by financial institutions, 29% (EUR 1.11 trillion) were issued by non-financial institutions, while the rest were issued by financial institutions (41%) and governments (29%).

Restriction of sample to French financial institutions holders and (French or foreign) non-financial firms issuers: We restrict our sample to these 1.11 trillion held by French financial institutions and issued by (French or foreign) non-financial firms. Those EUR 1.11 trillion are made of listed shares (ESA code of instruments F511, 54%), short-term debt securities (F31, 44%) and long-term debt securities (F32, 41%). They were mostly held by non-MMF investment funds (38%), insurance corporations (38%), commercial banks (14%), and to a lesser extent by money market funds (5%) and other financial corporations excluding financial vehicle corporations (5%).

Restriction to issuers whose turnover information is known: These EUR 1.11 trillion were issued by around 15000 non-financial companies, but they are highly concentrated in a few big non-financial companies that issued them (99% were issued by 3346 firms, 90% by 809 firms). Using the C4F database, we gather information regarding the issuers (turnover value and sectorial decomposition, enterprise value) - that will be used to compute their dependency scores and biodiversity footprints. Eventually, we are not able to find information for all the firms, hence the final sample (so-called "portfolio" in this paper) contains EUR 995 trillion of securities issued by 1126 firms, covering 89.6% of the initial sample of EUR 1.11 trillion.

A.1.2. Putting this data into perspective: Which share of the total asset of French financial institution's balance sheet does this "portfolio" represent?

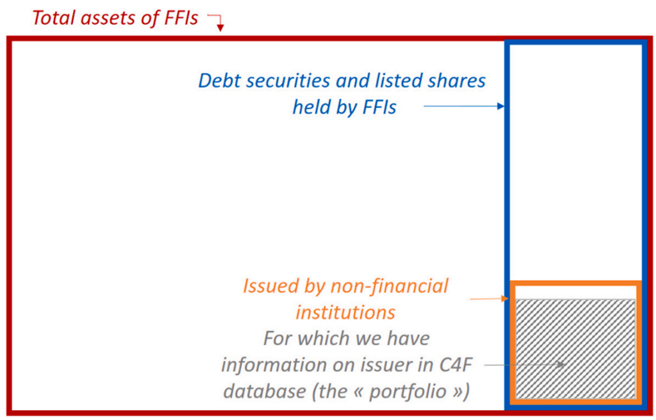


Fig. A1. Coverage of FFIs' total assets and total securities by the "portfolio" sample.
Source: Authors.

Our analysis covers the grey rectangle in Fig. A1 (EUR 995 trillion): debt securities and listed shares held by FFIs and issued by non-financial institutions, for which we are able to recover information regarding their issuer (turnover, enterprise value, etc.). As mentioned above, these represent 89.6% of the debt securities and listed shares held by FFIs in 2019Q4 and issued by non-financial institutions (orange rectangle). According to the SHS database, still in 2019Q4, those debt securities and listed shares issued by non-financial institutions (orange rectangle) represented 29% (1.11 trillion euros) of the debt securities and listed shares owned by FFIs (blue rectangle – 3.8 trillion euros) – the rest having been issued by governments and financial institutions. Finally, according to Banque de France data,[28] in 2021, the debt securities and listed shares held by the FFIs covered in our analysis (S122, S123, S124, S125 and S128) (blue rectangle) represented 23.8% of their total assets in their balance sheet (red rectangle). However, this figure varies with the type of financial institutions: Fig. A2 below shows for example that those securities only represented 9% of the assets held by commercial banks in 2021 (against 37% for loans). Therefore, we estimate that we are covering:

- $23.8\% \times 29\% \times 89.6\% = 6.1\%$ the total assets of the balance sheet of the French financial institutions.
- $29\% \times 89.6\% = 26\%$ of the securities and listed shares of French financial institutions.

[28] https://www.banque-france.fr/system/files/2023-07/detaillesemidefinitif2021.pdf

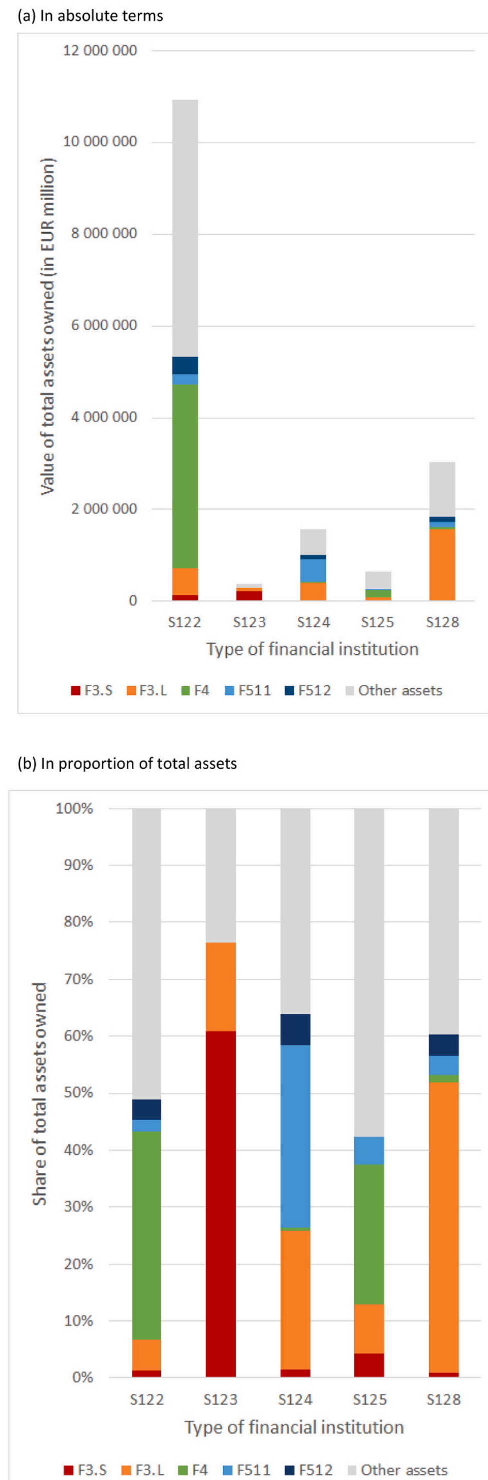


Fig. A2. Composition of assets by type of French financial institution - France, 2021.
Source: Compte de patrimoine financier semi-définitif, Encours, Actifs, 2021 (Banque de France) – Figure: Authors.
Lecture note: Assets: F3·S: Short-term debt securities, F3.L: Long-term debt securities, F4: Loans, F511: listed shares, F512: Non-listed shares - Financial institutions: S122: Deposit-taking corporations except central banks, S123: Money market funds, S124: Non-MMF Investment funds, S125: Other financial intermediaries, except insurance corporations and pension funds, S128: Insurance corporations.

A.2. Annex 2: Dependency scores

A.2.1. List of ecosystem services

Table A1
Ecosystem services included in ENCORE database.

Provisioning Services	Regulation and Maintenance Services
Ground water	Mass stabilization and erosion control
Surface water	Pest control
Genetic materials	Climate regulation
Fibers and other materials	Disease control
	Flood and storm protection
	Ventilation
	Filtration
	Pollination
	Dilution by atmosphere and ecosystems
	Bio-remediation
	Water flow maintenance
	Maintain nursery habitats
	Water quality
	Mediation of sensory impacts
	Soil quality
	Animal-based energy
	Buffering and attenuation of mass flows

A.2.2. Computation of upstream dependency scores

We recorded dependency scores in a matrix called D_{dir} of dimension $s \times d$ with s the number of sectors (163) and d the number of ecosystem services (21). To obtain upstream dependency scores per industries, we proceeded as follows. First, each coefficients of the indirect requirement matrix ($L^{-1} - I$, where L^{-1} is the classic Leontief inverse matrix obtained with the EXIOBASE input-output table) are first divided by the sum of its column in order to obtain the weight of each pairs of country-sector in the supply chain of sector *i*. The obtained matrix is called the normalized indirect requirement matrix and is written $\overline{L^{-1} - I}$. This matrix is then used to construct the matrices $D_{up,r}$ of "upstream dependency scores", also of dimension $s \times d$ for each regions *r*. The region-specific matrix $D_{up,r}$ is constructed as follows:

$$D_{up,r} = D_{dir}^{\intercal} \bullet \left(\overline{L^{-1} - I}\right)_r$$

where the $\intercal$ in exponent means the transposed of a matrix and the subscript *r* signifies that we only take the region *r* specific (163 × 163) part of the global (163*49 × 163*49) matrix. Symbol • is used to notate an element-wise multiplication (Hadamard product). Note that our method of computing upstream dependencies involves assuming that the total indirect dependency is a weighted average of the dependency of the sectors included in the entire value chain. One could think of different aggregation approaches, such as using the maximum dependency observed in the supply chain. However, in that case, as all sectors are supplied (to varying degrees) by all sectors in the input-output matrix, one would need to define a threshold (in terms of input share for example) below which sectors are excluded from the analysis. Otherwise, the indirect scores of sectors would all be equal to the direct score of the sector with the maximum direct score (most likely, a score of 100% - very high dependency). Given the difficulty to define such a threshold, we leave this to future research.

A.3. Annex 3: EXIOBASE sectors and their codes

Table A2
EXIOBASE sectors and their codes.

Sectors codes	Sectors names
PARI	Cultivation of paddy rice
WHEA	Cultivation of wheat
OCER	Cultivation of cereal grains nec
FVEG	Cultivation of vegetables, fruit, nuts
OILS	Cultivation of oil seeds
SUGB	Cultivation of sugar cane, sugar beet
FIBR	Cultivation of plant-based fibers
OTCR	Cultivation of crops nec
CATL	Cattle farming
PIGS	Pigs farming
PLTR	Poultry farming
OMEA	Meat animals nec
OANP	Animal products nec
MILK	Raw milk
WOOL	Wool, silk-worm cocoons
MANC	Manure treatment (conventional), storage and land application

(*continued on next page*)

Table A2 (*continued*)

Sectors codes	Sectors names
MANB	Manure treatment (biogas), storage and land application
FORE	Forestry, logging and related service activities
FISH	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
COAL	Mining of coal and lignite; extraction of peat
COIL	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
GASE	Extraction of natural gas and services related to natural gas extraction, excluding surveying
OGPL	Extraction, liquefaction, and regasification of other petroleum and gaseous materials
ORAN	Mining of uranium and thorium ores
IRON	Mining of iron ores
COPO	Mining of copper ores and concentrates
NIKO	Mining of nickel ores and concentrates
ALUO	Mining of aluminium ores and concentrates
PREO	Mining of precious metal ores and concentrates
LZTO	Mining of lead, zinc and tin ores and concentrates
ONFO	Mining of other non-ferrous metal ores and concentrates
STON	Quarrying of stone
SDCL	Quarrying of sand and clay
CHMF	Mining of chemical and fertiliser minerals, production of salt, other mining and quarrying n.e.c.
PCAT	Processing of meat cattle
PPIG	Processing of meat pigs
PPLT	Processing of meat poultry
POME	Production of meat products nec
VOIL	Processing vegetable oils and fats
DAIR	Processing of dairy products
RICE	Processed rice
SUGR	Sugar refining
OFOD	Processing of Food products nec
BEVR	Manufacture of beverages
FSHP	Manufacture of fish products
TOBC	Manufacture of tobacco products
TEXT	Manufacture of textiles
GARM	Manufacture of wearing apparel; dressing and dyeing of fur
LETH	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
WOOD	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials
WOOW	*Re*-processing of secondary wood material into new wood material
PULP	Pulp
PAPR	Re-processing of secondary paper into new pulp
PAPE	Paper
MDIA	Publishing, printing and reproduction of recorded media
COKE	Manufacture of coke oven products
REFN	Petroleum Refinery
NUCF	Processing of nuclear fuel
PLAS	Plastics, basic
PLAW	Re-processing of secondary plastic into new plastic
NFER	N-fertiliser
PFER	P- and other fertiliser
CHEM	Chemicals nec
RUBP	Manufacture of rubber and plastic products
GLAS	Manufacture of glass and glass products
GLAW	Re-processing of secondary glass into new glass
CRMC	Manufacture of ceramic goods
BRIK	Manufacture of bricks, tiles and construction products, in baked clay
CMNT	Manufacture of cement, lime and plaster
ASHW	Re-processing of ash into clinker
ONMM	Manufacture of other non-metallic mineral products n.e.c.
STEL	Manufacture of basic iron and steel and of ferro-alloys and first products thereof
STEW	*Re*-processing of secondary steel into new steel
PREM	Precious metals production
PREW	Re-processing of secondary precious metals into new precious metals
ALUM	Aluminium production
ALUW	Re-processing of secondary aluminium into new aluminium
LZTP	Lead, zinc and tin production
LZTW	Re-processing of secondary lead into new lead
COPP	Copper production
COPW	Re-processing of secondary copper into new copper
ONFM	Other non-ferrous metal production
ONFW	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
METC	Casting of metals
FABM	Manufacture of fabricated metal products, except machinery and equipment
MACH	Manufacture of machinery and equipment n.e.c.
OFMA	Manufacture of office machinery and computers
ELMA	Manufacture of electrical machinery and apparatus n.e.c.
RATV	Manufacture of radio, television and communication equipment and apparatus
MEIN	Manufacture of medical, precision and optical instruments, watches and clocks
MOTO	Manufacture of motor vehicles, trailers and semi-trailers
OTRE	Manufacture of other transport equipment

(*continued on next page*)

Table A2 (*continued*)

Sectors codes	Sectors names
FURN	Manufacture of furniture; manufacturing n.e.c.
RYMS	Recycling of waste and scrap
BOTW	Recycling of bottles by direct reuse
POWC	Production of electricity by coal
POWG	Production of electricity by gas
POWN	Production of electricity by nuclear
POWH	Production of electricity by hydro
POWW	Production of electricity by wind
POWP	Production of electricity by petroleum and other oil derivatives
POWB	Production of electricity by biomass and waste
POWS	Production of electricity by solar photovoltaic
POWE	Production of electricity by solar thermal
POWO	Production of electricity by tide, wave, ocean
POWM	Production of electricity by Geothermal
POWZ	Production of electricity nec
POWT	Transmission of electricity
POWD	Distribution and trade of electricity
GASD	Manufacture of gas; distribution of gaseous fuels through mains
HWAT	Steam and hot water supply
WATR	Collection, purification and distribution of water
CONS	Construction
CONW	Re-processing of secondary construction material into aggregates
TDMO	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessories
TDFU	Retail sale of automotive fuel
TDWH	Wholesale trade and commission trade, except of motor vehicles and motorcycles
TDRT	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods
HORE	Hotels and restaurants
TRAI	Transport via railways
TLND	Other land transport
TPIP	Transport via pipelines
TWAS	Sea and coastal water transport
TWAI	Inland water transport
TAIR	Air transport
TAUX	Supporting and auxiliary transport activities; activities of travel agencies
PTEL	Post and telecommunications
FINT	Financial intermediation, except insurance and pension funding
FINS	Insurance and pension funding, except compulsory social security
FAUX	Activities auxiliary to financial intermediation
REAL	Real estate activities
MARE	Renting of machinery and equipment without operator and of personal and household goods
COMP	Computer and related activities
RESD	Research and development
OBUS	Other business activities
PADF	Public administration and defence; compulsory social security
EDUC	Education
HEAL	Health and social work
INCF	Incineration of waste: Food
INCP	Incineration of waste: Paper
INCL	Incineration of waste: Plastic
INCM	Incineration of waste: Metals and Inert materials
INCT	Incineration of waste: Textiles
INCW	Incineration of waste: Wood
INCO	Incineration of waste: Oil/Hazardous waste
BIOF	Biogasification of food waste, incl. Land application
BIOP	Biogasification of paper, incl. Land application
BIOS	Biogasification of sewage slugde, incl. Land application
COMF	Composting of food waste, incl. Land application
COMW	Composting of paper and wood, incl. Land application
WASF	Waste water treatment, food
WASO	Waste water treatment, other
LANF	Landfill of waste: Food
LANP	Landfill of waste: Paper
LANL	Landfill of waste: Plastic
LANI	Landfill of waste: Inert/metal/hazardous
LANT	Landfill of waste: Textiles
LANW	Landfill of waste: Wood
ORGA	Activities of membership organisation n.e.c.
RECR	Recreational, cultural and sporting activities
OSER	Other service activities
PRHH	Other service activities
EXTO	Extra-territorial organizations and bodies

A.4. Annex 4: Exposure to transition "high-stake" firms and sectors

A.4.1. Portfolio exposure to firms depending on their footprint and intensity

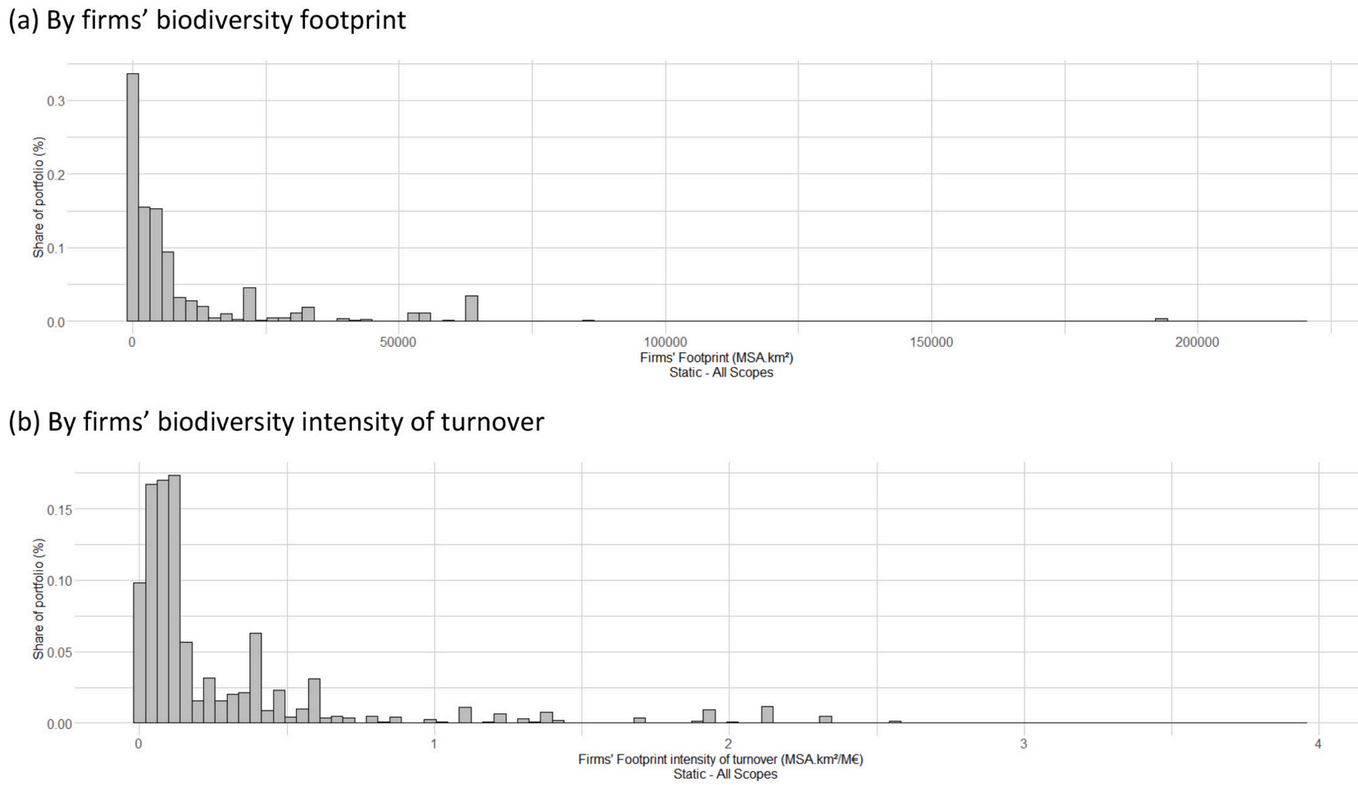


Fig. A3. Distribution of the value in the portfolio.
Source: Authors.

A.4.2. Sensitivity analysis of portfolio exposure to definition of transition "high-stake" sectors

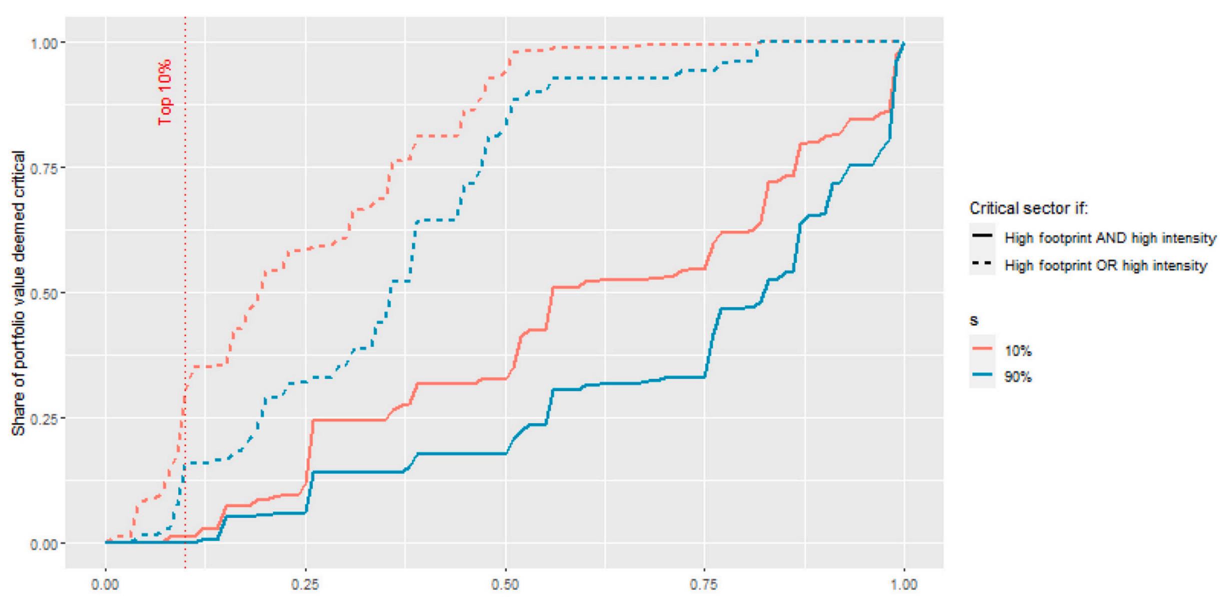


Fig. A4. Sensitivity of portfolio exposure to definition of "transition high-stake" sectors.
Source: Authors.

High-stake sectors: A sector becomes "high-stake" if it is in the top c% (in terms of intensity, footprint or both). The red line represents the threshold chosen to obtain our results, c = 10%. **Portfolio exposure**: if a company has more than s% of its turnover coming from high-stake sectors, then the total value of the securities it issued is deemed high-stake.

A.4.3. Portfolio exposure to biodiversity "transition-critical" sectors

Table A3
Portfolio exposure to biodiversity "transition-critical" sectors.

		Top 10% in terms of:	
		Direct footprint	Direct and Indirect footprint
Top 10% in terms of:	Both high footprint and high intensity	12 **critical sectors:** • **Cultivation of:** wheat (WHEA); cereal grains (OCER); vegetables, fruit, nuts (FVEG); oil seeds (OILS); sugar cane, sugar beet (SUGB); paddy rice (PARI) • **Farming of:** cattle (CATL); pigs (PIGS); other meat animals (OMEA); raw milk (MILK) • **Forestry**, logging and related service activities (FORE) • **Mining of:** coal and lignite; extraction of peat (COAL) **Portfolio exposure** to these sectors: Option a: 0% Option b: 0.2%	10 **critical sectors:** • **Cultivation of:** wheat (WHEA); cereal grains (OCER); vegetables, fruit, nuts (FVEG); oil seeds (OILS) • **Farming of:** cattle (CATL); raw milk (MILK) • **Forestry**, logging and related service activities (FORE) • **Processing of:** meat cattle (PCAT); food products (OFOD) • **Manufacture of:** wood and of products of wood and cork, except furniture; articles of straw and plaiting materials (WOOD) **Portfolio exposure** to these sectors: Option a: 0.9% Option b: 1.5%
	Either high footprint or high intensity	20 **critical sectors:** • **Cultivation of:** wheat (WHEA); other cereal grains (OCER); vegetables, fruit, nuts (FVEG); oil seeds (OILS); sugar cane, sugar beet (SUGB); plant-based fibers (FIBR); other crops (OTCR); paddy rice (PARI) • **Farming of:** cattle (CATL); pigs (PIGS); poultry (PLTR); other meat animals (OMEA); other animal products (OANP); Raw milk (MILK) • **Forestry**, logging and related service activities (FORE) • **Mining of:** coal and lignite, extraction of peat (COAL); copper ores and concentrates (COPO) • **Manufacture of:** wood and of products of wood and cork, except furniture; articles of straw and plaiting materials (WOOD) • Wholesale **trade** and commission trade, except of motor vehicles and motorcycles (TDWH) • **Biogasification of paper**, incl. Land application (BIOP) **Portfolio exposure** to these sectors: Option a: 0.1% Option b: 1.2%	22 **critical sectors:** • **Cultivation of:** wheat (WHEA); other cereal grains (OCER); vegetables, fruit, nuts (FVEG); oil seeds (OILS); sugar cane, sugar beet (SUGB); plant-based fibers (FIBR); paddy rice (PARI) • **Farming of:** cattle (CATL); pigs (PIGS); other meat animals (OMEA); Raw milk (MILK) • **Forestry**, logging and related service activities (FORE) • **Processing of:** meat cattle (PCAT); vegetable oils and fats (VOIL); dairy products (DAIR); other food products (OFOD) • **Manufacture of:** beverages (BEVR); wood and of products of wood and cork, except furniture; articles of straw and plaiting materials (WOOD) • Other **Chemicals** (CHEM) • **Construction** (CONS) • **Hotels and restaurants** (HORE) • **Health** and social work (HEAL) **Portfolio exposure** to these sectors: Option a: 24.1% Option b: 38.5%

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