Environmental responsibility and exposure of finance: combining Environmentally-extended Input-Output and Balance Sheet approaches

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Abstract

Finance both contributes to environmental degradation and is vulnerable to environmental degradation. This article sets the methodological groundwork for assessing both concerns in an integrated macro-accounting framework. It is presented how the combination of Environmentally extended Input-Output analysis and balance sheet methods and data can be used to evaluate the contribution of finance to environmental degradation (responsibility) and the vulnerability of finance to environmental risks (exposure). In doing so, the article contributes to the development of a disaggregatted ecological macroeconomy integrating monetary and biophysical flows and stocks.

I Introduction

The causal relations between an industrial metabolism and its surrounding environment are twofold: the economy contributes to and is vulnerable to environmental degradation (Ayres and Simonis, 1994; Haberl et al., 2019). Environmentally-extended Input-Output (EIO) analysis is one of the main methods for assessing the interdependencies between industrial activity and the environment (Wiedmann et al., 2007; Murray and Lenzen, 2013). However, a comprehensive understanding of the social metabolism must integrate all its socio-institutional aspects (Fischer-Kowalski and Weisz, 1999). The financial system and monetary debt relationships recorded on the balance sheets (BSs) of the economy represent one such aspect. The monetary theory of production makes indeed clear the importance of studying monetary flows and stocks at the macroeconomic level (Graziani, 1989, 2003; Keen, 2009; Sawyer and Passarella, 2017). But although Fontana and Sawyer (2016) stress the embedding of the monetary circuit in its biophysical environment, the financial and the socio-metabolic systems are usually studied separately. Such a disconnection

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is unfortunate. As Hagens (2020, p.11) states, "the energy/credit/growth dynamic is the least understood but most important phenomenon driving the current global economic and ecological situation". Finance partially drives economic activity and is exposed to environmental shocks through their effect on the activity.

This paper presents an integrated macroeconomic framework capable of accounting for the contribution and the vulnerability of finance to the biophysical environment. In that purpose, the article asks how to assess the environmental responsibility and exposure of financial assets by combining methods and data from EIO and BS approaches.

The notions of responsibility and exposure of finance allow to distinguish the two main causal relationships existing between finance and the environment (see Figure 1). On the one hand, indebtedness is a necessary condition, and thus a driver, of production and socio-metabolic processes. Monetary regimes and financial system's particularities have implications for the metabolic regime that will prevail in a historical context (Jerneck, 2017; Cahen-Fourot, 2020). On the other hand, feedback loops from the environment affect the financial system. Indeed, environmental threats are increasingly recognized by economists and the financial sector as a risk for the financial system (Carney, 2015; Battiston et al., 2021). These justify the relevance of empirically evaluating the environmental contribution and vulnerability of finance. Moreover, as the concept of "double materiality" will make clear (European Commission, 2019), since a money advance is at the same time an economic capacity to motion physical things and a liability resting on physical factors, both concerns are interrelated: environmental degradation is a cause of environmental vulnerability. It is therefore relevant to address both concerns within a common accounting and modeling framework.

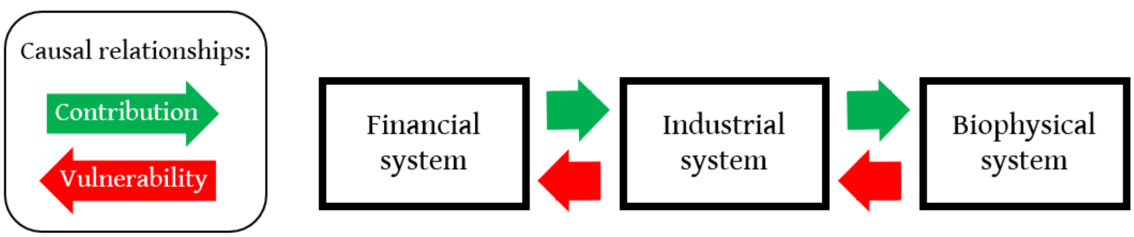

Figure 1: *Contribution of finance to environmental degradation and environmental vulnerability of finance*

This paper aims to establish that such a framework can relevantly be based on the combination of EIO and BS approaches. In this regard, the fundamental information an EIO table provides are industries' productive linkages and environmental footprints, from which can be derived the environmental responsibilities and vulnerabilities of industrial sectors (Lenzen and Murray, 2010; Chen et al., 2014). For its part, the fundamental information BSs provide are agent's liabilities, reflecting on the one hand the funding structure that enables the activity to proceed, and representing on the other hand some promises to pay in the future on which other assets in other balance sheets depend (Mayer, 1988; Allen et al., 2002). The basic intuition developed in this paper is therefore that, when combined to the examination of stock variables in the balance sheets of the economy, the analytical and empirical power of EIO analysis in assessing environmental responsibility and exposure can relevantly be extended to finance. Ideally, such a combination will make it possible to provide a complete description of the biophysical, industrial and financial interrelationships involved in the metabolic process of society. This paper is a first attempt of generalization that paves the way for further methodological improvements, in-depth empirical analyses and database development.

In this way, the framework sets up the methodological groundwork for applying to the environmental domain the two famous questions raised by Copeland (1949, p. 254) who argues for social accounting:[1] when the metabolic rate of the economy increases, where does the money come from to finance the underlying activities? And when the access to ecosystem services declines, what does the money that depend on them become? While ecological macroeconomics (Rezai and Stagl, 2016) mainly focuses on aggregate relationships for now, the EIO-BS framework proposed in this paper could provide a solid foundation for constructing an ecological macroeconomy combining monetary and physical flows and stocks in a disaggregated fashion.

The content of the paper is as follows. Next section reviews the literature. Sections III and IV interpret the notions of environmental responsibility and exposure of finance (with an emphasis on transition risks) in a framework combining EIO and BS approaches, and provide methods for assessing them in such a framework. Section V illustrates the methodological contribution in an empirical case study. Section VI concludes.

II Literature reviews

The paper is based on two strands of the literature related to the issues of environmental responsibility and exposure. The first strand relates to the application of the EIO approach to these issues. The second deals with the financial dimension of these issues.

i EIO analysis of environmental responsibility and exposure

Input-Output (IO) analysis of industrial networks (Leontief, 1919; Miller and Blair, 2009) is the main method to empirically study productive interdependencies at the macroeconomic level (Akhabbar, 2019). A Multi-Regional IO (MRIO) approach allows for including inter-regional/national relations in the picture (Leontief and Strout, 1963; Hewings and Jensen, 1987). Regarding the environmental issue, IO techniques have long been mobilized to account for the economy-wide throughput (Ayres and Kneese, 1969). In this respect, Environmentally-extended MRIO (EMRIO) analysis (Turner et al., 2007; Wiedmann et al., 2007) now constitutes a well-established methodology consistent with the System of Environmental Economic Accounting (Chow, 2013; United Nations, 2017, chap.III) and with other methods of material accounting like Material Flow Accounting (MFA) (Weisz, 2006; Liu et al., 2021) and Life Cycle Assessment (LCA) (Suh, 2004; Majeau-Bettez et al., 2016).

The first purpose of EIO assessment is to identify what activities, economic agents or countries contribute to ecological degradations (Wiedmann et al., 2015), that is what their environmental responsibilities are (Lenzen and Murray, 2010). The EIO account of responsibility derives directly from the accounts of direct or indirect environmental footprints (Rodrigues et al., 2006; Steinmann et al., 2017; Liang et al., 2017). In practice, responsibility assessment can be used to describe channels of environmental degradation (Wiedmann et al., 2015; Pothen and Reaños, 2018; Castellani et al., 2019), to explain historical evolution (Zhang et al., 2014; Shi et al., 2017; Jiborn et al., 2018; Hardt et al., 2018; He et al., 2020) and to identify leverage points of mitigation efforts within the economy (Wiedmann and Barrett, 2013; Galli, 2015; Giljum et al., 2016; Beaussier et al., 2019; Aguilar-Hernandez et al., 2018; Vercalsteren et al., 2020). It can also assign political responsibilities as a tool in global environmental governance (Peters and Hertwich, 2008; Wei et al., 2014; Dalmedico and Aykut, 2015). For instance, EMRIO tables were used to describe the structural environmental deficit of the global North (Peng et al., 2016; Tukker et al., 2016;

[1] The original questions are: "when total purchases of our national product increase where does the money come from to finance them? When purchases of our national product decline, what becomes of the money that is not spent?"

Dorninger et al., 2021). Methods like decomposition analysis (de Boer and Rodrigues, 2020; He et al., 2020) help to explain changes in environmental impacts, while structural path analysis (Giljum et al., 2016; Wieland et al., 2018) allows for identifying the supply-chain layers (or steps) where indirect environmental degradation occurs.

EIO analysis also applies to the identification of activities exposed to environmental risks. On the one hand, the EIO approach can be used to study so-called physical risks (Chen et al., 2014; Henriet et al., 2012; Oosterhaven and Többen, 2017; Khanna and Bakshi, 2009; Yu et al., 2014; Aviso et al., 2015; Busch, 2020), emerging from the physical impact of the environment on the economy (Tol, 2009; Hsiang et al., 2017; Diffenbaugh and Burke, 2019; Kemp-Benedict et al., 2019). On the other hand, the environment has also an indirect effect through the attempt of communities to attenuate their environmental impact, leading to so-called transition risks that materialize in policy, preference, or technological changes (Farrell and Brandt, 2006; Blonz et al., 2012; Miller et al., 2013; Blazejczak et al., 2014; Capellán-Pérez et al., 2017; Semieniuk et al., 2021). EIO tables provide useful information to assess the macroeconomic implications of such changes: primarily productive linkages through which transition shocks propagate, and second, environmental footprints that help identifying the agents targeted by mitigation efforts. For instance, Choi et al. (2010), Hebbink et al. (2018), Devulder and Lisack (2020) or Mongelli et al. (2009) assess the indirect effects of a carbon tax on economic sectors embedding emissions. Cahen-Fourot et al. (2021) are looking for the stranding cascade of physical capital following the abandonment of fossil fuel inputs. Bastidas and Mc Isaac (2019) study the employment effect of a low-carbon transition approximated by an optimization procedure based on carbon footprints. Perrier and Quirion (2017), Montt et al. (2018); Malerba and Wiebe (2021) and Blazejczak et al. (2014) study the overall employment impact of exogenous transition scenarios.

ii The environmental responsibility and exposure of finance

ii.1 Responsibility

In the public sphere, the role of finance as a problem or as a salvation to the environmental challenge is now a widely discussed topic. But despite some recent exceptions (see Hardt and O'Neill, 2017; Mazzucato and Semieniuk, 2018; Svartzman et al., 2019; Ament, 2020, for instance), it has not been as important in industrial ecology or even in ecological economics. What might explain that state is the conception that still prevail in mainstream economics, according to which the contribution of money and finance is for the rest of the economy more or less neutral (Lucas, 1972). For instance, according to the Modigliani and Miller (1958) theorem, the type of financing instrument issued by a company does not matter from an economic point of view. If it is admitted that certain types of financial actors can stand out to overcome imperfections (Hall, 2002),[2] the mainstream model of 'directionality' of innovation for instance (Acemoglu, 2002), does not pay any attention to finance (only prices and market sizes affect the direction of technical change). This notably applies to the environmental version of the model (Acemoglu et al., 2012, 2016; Jaffe et al., 2005).

Nevertheless, other views precisely emphasizes the importance of finance and debt relations in shaping economic and industrial evolution, mainly Post-Keynesian and Neo-Schumpeterian authors (Graziani, 2003; Mazzucato and Wray, 2015; Hall et al., 2017). Both traditions emphasize the "enabling role" of finance in allocating purchasing power. They are notably synthesized in

[2] Especially when it comes to the financing of innovation. For instance the job of the government is to overcome underinvestment in research due to the positive externality of knowledge, and the purpose of venture capitalists is to overcome information asymmetries that led to underinvestment into product development by new firms (Hall and Lerner, 2010)

Minsky's work. Minsky (2004, p.96) called the "survival constraint" the settlement system that send a key signal to every individual about his current standing in the system. In this view, "only that which is financed can happen" (Minsky, 1990, p.66) and creditors thus call the shots in enforcing the survival constraint. Contrary to what the Modigliani-Miller theorem suggests, it is therefore "impossible to draw a meaningful investment demand function without simultaneously specifying the liabilities that will be emitted" (Minsky, 1967, p.47). Who create and manage money thus fashion the physical world by choosing whether or not to provide purchasing power. Works such as Perez (2002) look for instance at the central role played by finance in allowing new technological paradigms to take off. And the purpose of an important strand of the corporate finance literature is precisely to assess empirically how external financing and the characteristics of financial systems (importance of certain actors, legal frame...) affect patterns of investment, accumulation and development (Frank and Sanati, 2021; Mayer, 1988; Taggart, 2009; La Porta et al., 2000; Levine, 2005). Ultimately, in this view, "[t]he financial system determines what kind of industrial management an economy will have" (Bezemer and Hudson, 2016).

Regarding the environmental issue, the recognition of such an enabling role of finance has led authors to study how financial systems affect the way the economy uses natural resources and releases wastes. On the theoretical side, Godin et al. (2017), for instance, model how the pure apathy of financial actors toward green investments affects the transition to a low-carbon economy.[3] On the empirical side, Mariana Mazzucato and Gregor Semieniuk recently studied the extent to which different sorts of investors financially participated to the evolution of the energy sector, i.e. "the 'direction' of innovation that financial actors create" (Mazzucato and Semieniuk, 2018, p.8).[4] Ultimatly, recognizing the performative power of finance as well as the biophysical content of any economic activity leads to acknowledge that "debt is a social construct with physical consequences" (Hagens, 2020, p.7).

Based on such a premise, many empirical analyses investigate the physical content of financial assets. The environmental responsibility of an investor is envisaged as the environmental impact of the funded activities. The issue directly relates to investors' Environmental, Social, and Corporate Governance (ESG) responsibility (see Scholtens and Dam, 2007; Jayashankar et al., 2015). For example, by combining assets data with firm-level CO_2 emissions information, Boermans and Galema (2019) ask whether pension funds are "actively decarbonizing their portfolios". Other examples such as Schücking et al. (2011), Petherick (2012) or Portfolio Earth studies (Portfolio Earth, 2021, 2020) look at the environmental burden of banks' credit ('dirty money'). This type of assessments has also been applied to policymakers, including for instance Matikainen et al. (2017) who assess the "climate impact of quantitative easing" of the European Central Bank (see also Dafermos et al., 2020b).

Some studies, such as those cited above, already evaluate the environmental contribution of financial actors. And EIO tables have recently been combined with financial data for this purpose. CDC (2018), for instance, analyzes the biodiversity impact of portfolios in such a way. Nevertheless, the notion of environmental responsibility of financial actors is still in its infancy, and the potential of combining EIO tables with BS data as a means of analyzing the financial side of the social metabolism has yet to be explored. Section III of this paper attempts to provide a

[3]See also Kemp-Benedict (2018) or D'Orazio and Valente (2019) for examples of theoritical models where finance matters for the evolution of economic system in regard to the environment.

[4]Other empirical studies also describe the industrial and environmental implications of financial system's configuration. Drawing on examples from South Africa and Mexico, Baker (2021) describes the frameworks and logics of finance in utility-scale renewable electricity generation as a key aspect of the political economy of the energy transition. Besides that, the specific role of financialization was also put forward. In a key study, Jerneck (2017) compares the US and the Japan cases where in the latter the financing of the photo-voltaic sector was not passed to equity-based finance and then continued to invest in physical capacities. See also Assa (2020) and Kovacic et al. (2018) who study the role of financialization for socio-metabolic patterns.

solid foundation for defining and measuring financial responsibility in a unified representation of biophysical, industrial and financial realities.

ii.2 Exposure

Unlike environmental responsibility, the environmental exposure of finance has already been widely studied for several years. Indeed, as global environmental threats became increasingly recognized, awareness of environmental risks for financial stability grew (Carney, 2015; NGFS, 2019). This theme then became important in economics and finance (Migliorelli and Dessertine, 2020) as well as for monetary authorities (Svartzman et al., 2021). The main issues being discussed are the identification of assets based on activities threatened by physical or transitional risks, and the extent to which this kind of vulnerability could translate into systemic or macroeconomic issues (Mercure et al., 2018; Monasterolo et al., 2019). For climate risks, Battiston et al. (2021) summarize the problem as follows:

"*[T]he fact that the physical effects of climate change and the low-carbon transition have fundamental implications for a range of sectors in the economy makes climate risk relevant for the financial stability of individual institutions. Further, because of the correlation of the impacts and the interconnectedness of institutions and economies, climate risk is also relevant for the financial stability at both national and global level*" (Battiston et al., 2021, p.2).

Financial *physical* risks constitute one side of the picture, emphasizing that physical shocks might translate into adverse financial consequences (Dietz et al., 2016; Dafermos et al., 2018; Lamperti et al., 2019). On the other side, the notion of financial *transition* risks emphasizes that transition shocks (changes in policies, technologies or preferences) could lead to assets stranding (Caldecott, 2018; Dericks et al., 2018; Monasterolo and De Angelis, 2020; van der Ploeg and Rezai, 2020) and adverse financial consequences (Bank for International Settlements, 2020; Semieniuk et al., 2021). For instance, Battiston et al. (2017) study second-round effects of real transition shocks inside finance by examining networks of interlinked balance sheets. The recent ECB's blog post *Shining a light on climate risks: the ECB's economy-wide climate stress test* (by Luis de Guindos, Vice-President of the ECB) insists on the systemic potential of both physical and transition financial risks.

IO tables and BS data have recently been combined to study the role of industrial interconnections for financial returns and stability (Herskovic, 2018; Grant and Yung, 2019; Gofman et al., 2020). Some studies already assess environmental risks in this way, looking at how environmental shocks affect the financial system by impacting financial balances all over the industrial network (Vermeulen et al., 2021; Godin and Hadji-Lazaro, 2022; Allen et al., 2020). However, no effort has yet been made to clarify the conditions under which this general framework can be used, and the variety of possible sub-approaches therein. This article attempts to accomplish this in section IV.

III Financial responsibility in an EIO-BS approach

i Defining the environmental responsibility of financial assets

A given industrial metabolism generates "effective" quantities of environmental degradation. These quantities are biophysical flows of environmental footprints, representing inputs (resource) or outputs (waste).[5] The sum of all footprints determines the metabolic rate of the economy (the

[5]To be distinguished from the Wackernagel and Kitzes (2019)'s notion of ecological footprint, who define it as "a resource accounting tool that measures the amount of the Earth's regenerative capacity (or 'biocapacity') demanded by a given activity" (page 270). Here, we do not refer to carrying capacity but only to resources uses and wastes emissions.

overall level of material use and emissions per unit of time).

Any effort to mitigate the environmental impact of an industrial system implies identifying the actors contributing to it by assigning to them a quantity of footprint. Within an industrial metabolism, multiple actors can be considered as causing one same unit of *effective* footprint. Indeed, although a considered flow of resource intake or waste emission over a given period of time is unique, the number of actors with agency power over it is multifaceted. Here, we distinguish between the level of contribution and the level of responsibility assigned to each economic agent. *Contributions* are equally assigned to all the actors involved in causing a given quantity of effective footprint. The contribution of each of these actors equal the amount of the effective footprint for which they are involved. The sum of all contributions thus amounts to the effective level of footprint considered times the number of actors contributing to it - implying multiple counting for one unit of effective footprint. Mapping contributions helps identifying all the agents having a potential agency power over a given level of environmental degradation. *Responsibilities* are shares of an effective level of footprint distributed to contributing actors according to a chosen regime of attribution. A regime of attribution weights the respective responsibility shares of each contributing actors (see a method in Gallego and Lenzen (2005) for instance), and necessarily involves value judgment (Lenzen et al., 2007). The sum of all responsibilities equates the effective level of footprint considered - double-counting is thus avoided. Assessing responsibilities serves notably to design policies aimed at intervening upon responsible actors.

Any identification method anchored in the National Accounts allocates contributions or responsibilities to accounting units. In the so-called "real economy", units sell and purchase items. The corresponding monetary flows (or operations) are recorded in their income and expense accounts (accounts 6 and 7 under the International Financial Reporting Standards (IFRS)). Based on the operations recorded in these accounts coupled with environmental extensions, contributing units are identified as those who pollute directly, those who use polluting goods by purchasing them (upstream), and those who enable the pollution by selling intermediate goods to polluting units (downstream) (Tukker et al., 2018; Marques et al., 2012). The contribution levels allocated to all these actors equally amount for each of them to the effective level of footprint considered. Responsibilities are shared among contributing units according to the chosen regime of attribution. The attribution regime can, for example, be based on an evaluation of the power relations existing between each of the agents (Lenzen and Murray, 2010). Whether we are interested in assigning contributions or responsibilities, we speak of "real footprints" as the accounting transactions involved in the environmental degradation take place in the so-called "real" economy, or more precisely, are recorded in the income and expense accounts.

Accounting units not only sell and purchase goods and services, they also own and owe assets and liabilities. Corresponding stocks are recorded in their balance sheet accounts (accounts 1 to 5 under the IFRS). The assets side of the balance sheet depicts the physical or financial stock of capital that is owned. The liabilities side depicts monetary advances owed. These advances represent purchasing power enabling agents to acquire the assets which make them able to carry out economic activity.[6] As "Schumpeter (1934) emphasized, credit is not a “factor of production,” but a precondition for production to take place" (Bezemer and Hudson, 2016, p.747). The agents who grant these advances thus "financially" participate the activity at stake and all its associated consequences, particularly environmental.

Investors, whatever their type, contribute to environmental degradation when they have allocated funds (purchasing power) to agents to whom a real footprint has been assigned. For a given level of footprint assigned to an accounting unit in the real economy, *financial contributions* are assigned equally to all the financial assets that correspond to liabilities recorded in the balance

[6] See for instance the related concept of "productive credit" developed by Bezemer and Hudson (2016).

sheet of the first unit. Stated differently, the environmental contribution of a financial asset (and therefore of its holder) coincides with the real footprint of the unit who issued the concerned title. Contributing holders may be financial institutions that have lent funds or purchased bonds and stocks, but they can also be non-financial companies or households that hold financial assets as long as these assets correspond to liabilities owed by polluting agents. *Financial responsibilities* are shared among contributing assets based on a financial attribution regime. The environmental responsibility of a financial asset depends on the relative weight attributed to this asset among all the assets issued by the polluting unit. A financial attribution regime can, for example, be based on an evaluation of the enabling capacity provided by each of the issued titles. One could, for example, consider that the enabling capacity granted by a long-term loan, given its longevity and repayment terms, is greater than that of a short-term commercial debt. Whether we are interested in assigning financial contributions or financial responsibilities, we speak of a "financial footprint" while the accounting stocks involved in this causal relation are recorded in balance sheet accounts.

ii Measuring financial responsibility

Given the above definitions, any quantitative measure of financial contributions or responsibilities must reflect how the economic activities to which a real footprint is attributed are financed. It is worth mentioning that far from trying to monetize biophysical flows, the point here is, on the contrary, to evaluate the biophysical content of titles denominated in monetary terms.

This paper proposes to quantitatively capture the environmental contribution or responsibility of a financial asset through the notion of “Financial Footprint" (FFP). The metric assigns a flow of footprint recorded in a given period to a financial stock that exists in the same period. The footprint assigned to an asset is formulated as a quantity per year for instance. The notion of FFP considers the real footprint of a polluting entity as financially embedded in the funding instruments issued to finance its activity. Once real footprints are assigned (either as real contributions or as real responsibilities), financial footprints are allocated (either as financial contributions or as financial responsibilities).

Formally, the scalar of financial footprint, $ffp_{a,i}$ (expressed in physical quantity) of a financial instrument a issued by a unit i can be calculated by combining the unit’s real footprint with the unit’s funding structure, as follows:

$$ffp_{a,i} = rfp_i . \max\{\delta; \frac{\alpha_{i,a} m_{i,a}}{\sum_k^K \alpha_{i,k} m_{i,k}}\} \tag{1}$$

, where rfp_i is the real footprint of unit i recorded in a given period, δ is a dummy variable taking either the value 1 for the study of financial contribution or 0 for the study of financial responsibility, $m_{i,a}$ is the book value of the funding instrument a in unit i’s liabilities, K is the number of instruments issued by i, and $\alpha_{i,a}$ is the share of financial responsibility assigned to the asset a issued by i (with $\sum_k^K \alpha_{i,k} = 1$). If, for instance, we assume no difference in the enabling capacity provided by each unit of monetary advance, we would have $\alpha_{i,a} = \frac{1}{K}$ for all instruments a issued by i. In this case, the real responsibility is simply shared among financial instruments according to their monetary share in the unit’s funding structure. This corresponds to the financial attribution regime chosen in the case study of section V. It would, however, be necessary to differentiate weights for different types of financial instruments if one considers that the financial capacity they provide is different.[7]

In this conception, whether looking at contributions or at responsibilities, the financial footprint

[7] The financial attribution regime to be adopted in specific cases is a point to be discussed further in future researches.

is superimposed on the real footprint. The sum of the financial footprints assigned to the assets issued by a particular unit amount to a multiple of the footprint assigned to this unit. When looking at financial contributions, this multiple is equal to the number K of instruments issued by the unit. In mathematical terms, we have $\sum_k^K ffp_{k,i} = K.rfp_i$ if $\delta = 1$. This reflects the objective of identifying all the (financial) agents having agency power over a given quantity of real footprint formerly assigned. When looking at financial responsibility, this multiple is equal to unity. We have $\sum_k^K ffp_{k,i} = rfp_i$ if $\delta = 0$. It is indeed necessarily the case while the numerator of the fraction in equation 1 is a subset of its denominator. One same unit of footprint is thus assigned to an issuer (under the item "real") *and* to some asset holders (under the item "financial"). It reflects a conception in which the nature of the contribution is different whether one economically or financially participates to environmental degradation. This logic matches the rationale of the "total carbon footprint" index of the TCFD (2017), intending to measure "the footprint associated with a portfolio“, or the rationale of the Global Biodiversity Score of CDC (2018).[8] Nevertheless, in order to avoid double counting, it would of course be possible to weight real footprint against financial footprint.

From the point of view of this metric, what "greening" a particular financial system means become clearer. Whether one is interested in its contribution or its responsibility, mitigating the footprint of a financial system consists in reducing the FFP assigned to the assets that compose this financial system. In such an aim, it is obviously useful to understand the industrial and financial network underlying FFPs in an integrated picture.

iii Deriving an integrated picture of financial responsibility from an EIO-BS approach

The empirical estimation of FFP is independent from the particular type of environmental and financial data being used. The only criterion to respect is consistency between the two databases, i.e. accounting units must be covered at the same scale. For example, if we know the financing structure of a company and the quantity of greenhouse gases the company emits, we can attribute these emissions to the different instruments issued by the company. The same logic applies to a nation as a whole for instance.

The method proposed in this paper combines EIO and BS data in an empirical framework at the industry level. EIO tables allows estimating the real footprint of industries (rfp_i in equation 1), while balance sheets data differentiated by industries inform on the financial instruments used to finance their activity ($m_{i,a}$ in equation 1).[9] Given available data, accounting practices, and empirical methods, this scale allows providing a comprehensive and integrated picture of financial responsibilities in a consistent framework.

The real side

On the real side of the picture, environmental stressors and productive inter-linkages depicted on EIO tables are used to attribute real environmental footprints. Contributions are assigned

[8] However, both these indices use assets' market values. Yet, market value includes wealth effects that mask the actual contribution of the asset to the financing. Imagine the case of an asset worth 100 at book value but then valued at 200 at market value. According to the market value it would appear to have contributed much more to the financing, while in fact it has only contributed 100. If available, the metric should use financial stock's book values.

[9] Industries do not themselves emit financial titles. In reality, accounting units are habitually firms. However, the industries themselves do not pollute either. Empirical analysis is always based on a arbitrary decomposition and aggregation of reality. Industry-level balance sheet data is one way to break down the complexity of the overall patrimonial reality.

to all the sectors involved directly, upstream or downstream in a particular amount of effective footprint. Responsibilities are shared among these sectors either on the basis of a specific regime of attribution or on the basis of one of the four usual attribution principles (see a review in Piñero et al., 2019). The "producer-based" principle assigns all the responsibility to the industry that directly generates it. The "consumption-based" principle assigns all the (upstream) responsibility to final demand industries (Peters, 2008; Hertwich and Wood, 2018). The "income-based" principle assigns all the (downstream) responsibility to industries according to income generation (Lenzen and Murray, 2010; Marques et al., 2012; Liang et al., 2017). And the "value-added approach" assigns all the responsibility according to the generation of value-added (Piñero et al., 2019). Whatever the approach chosen to assign real footprints, financial footprints are then allocated to the assets that finance the concerned sectors, following equation 1.

In addition to assign footprint to financial assets, the approach allows for documenting the value-chains underlying assets' footprint. The value-chain underlying the footprints embedded indirectly in an asset corresponds to the polluting network operating upstream or downstream from the funded industry. The EIO approach is well equipped for assessing such networks, especially thanks to structural path analysis (Giljum et al., 2016; Llop and Ponce-Alifonso, 2015; Wieland et al., 2018), or geographical analysis (Wiedmann et al., 2007; Marques et al., 2013). As such, the approach can give sight to assets holders or policymakers on the actions to be pursued in the aim at mitigating the footprint financially embedded in their portfolio or financial system. Indeed, the industrial units underlying a FFP correspond to levers in the real economy that an investor should, if possible, act on to mitigate the footprint embedded in its assets. For indirect footprint, the mitigation levers at the disposal of an asset holder are indirect as he only can exert pressure on the funded activity to stop participating to a particular value-chain. We can expect for instance that the less concentrated is the footprint and/or the more distant is the polluting layer from the funded sector, the less agency power an investor has to mitigate the footprint indirectly embedded in its assets.

The financial side

On the financial side, BS data are used to assess the financing instruments issued by polluting sectors and held by financial actors. In that aim, an industrial breakdown of BS data, complying with the EIO table, must be ensured. BS data must describe either liabilities at the industry level (describing how industries owe different types of debt and securities - see, for instance, European Central Bank (2015) or Stats SA (2019)), or assets in portfolios differentiated by industries (describing how investors hold assets issued by firms differentiated by industrial sectors - see, for instance, European Central Bank (2018) or Bureau Van Dijk Orbis database). In the first case, FFP is assigned to the funding instruments (liabilities) issued by industries. In the second case, FFP is directly allocated to assets and their holders.

Whether using liability or portfolio data, once it is known that an instrument or asset is issued by a certain sector, measuring its environmental contribution is directly possible with both types of data. The measurement of financial contributions indeed derives directly from the footprint of the sector that issues the corresponding assets. When studying financial responsibility, a database recording liabilities emitted by sectors is preferable. Indeed, knowing the entire financing structure of the sectors, the calculation of the FFP from the equation 1 is straightforward. On the contrary, by merely looking at portfolio (asset) databases, which usually only cover a limited set of asset holders, the actual financing structure of polluters cannot be fully estimated. Nevertheless, since $\sum_k^K \alpha_{i,k} m_{i,k}$ in equation 1 equals the total size of the sector i's BS, the calculation of financial responsibility can still be derived from portfolio databases if the total size of the sector's BS is known. Ideally, combining sectors' liabilities and holders' assets data would make it possible to both decompose the whole financial responsibility within issued instruments and identify the holders to whom financial responsibility should be attributed.

Furthermore, shouldn't financial footprint also be earmarked to the "second order" assets which fund the agent to whom the first order financial footprint is assigned? It should be if one considers that this second asset also (indirectly) contributes to the financing of the footprint. By contemplating cross detentions of assets, we could identify "financially indirect" financial footprint. That is, the footprint embedded in the assets used as liabilities by the holders of the assets used as liabilities by polluters. As discussed in Klein (2003), a full integration of IO and Flow-of-Funds (FoF) data (Copeland, 1949; Tsujimura and Tsujimura, 2019) would be beneficial in this respect. By integrating EIO matrices and Financial Social Accounting Matrices (or, assets-liability matrices à la Aray et al. (2017) or Tsujimura and Mizoshita (2003)) - following the work of Stone (1966) who first proposed to convert FoF accounts into square matrices, a complete and consistent picture of ecological, industrial and financial stocks and flows linkages could be provided in matrix format. In this manner, we would be able to consider all the channels of financial contributions involved in the financing of environmental degradation. And if one wanted to measure indirect financial responsibilities without double counting, then intra-financial weighting factors should be used.

An integrated picture

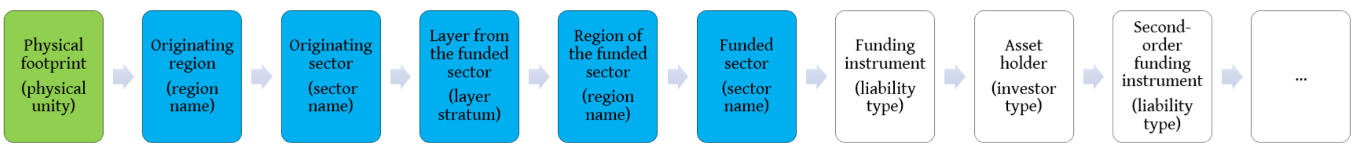

Figure 2: *Co-contribution channels across the socio-monetary metabolism*

Ultimately, iterations in both the financial and the real sides would allow for the comprehensive description of what could be named the "*socio-monetary metabolism*", seen from the perspective of environmental footprint: a complete picture of biophysical, industrial and financial interrelationships involved in the metabolic process of society. The scheme in Figure 2 summarizes the main information that an EIO-BS framework could combine. It is presented how contributions for a given level of footprint (expressed as a physical quantity) would be accounted for from the biophysical system (in the green box) through the industrial system (in blue boxes) to the financial system (in white boxes). From left to right, the physical footprint (first box) occurs due to an activity in a particular sector located in a specific region (boxes 2 and 3). The activity at stake is positioned at a particular layer in the value-chain of the funded activity considered (boxes 4). This funded activity operates in a certain region and in a certain sector (boxes 5 and 6). This sector finances itself by a particular funding structure that implies financial footprints embedded in the corresponding instruments (boxes 7). Those liabilities have their counterparts in holders' balance sheets as assets to which assign the financial footprint (boxes 8). The asset owners have themselves issued liabilities based on other assets to whom assign indirect financial contributions (boxes 9), etc... Section V provides such a picture for Greenhouse Gas emissions in the case of France.

IV Financial exposure in an EIO-BS approach

i Defining the environmental exposure of financial assets

Through physical and transition shocks, the biophysical environment affects economic performances which can lead to financial stress and instability. At the origin of financial instability, financial stress manifests itself in unexpected money shortages (Allen and Wood, 2006), emerging from the incapacity of some agents to fulfill repayment commitments or profitability anticipations (Beaver, 1966; Lin, 2009). Such an inability materializes in non-performing credits or assets devaluation, plus second order effects inside the financial sector (Allen and Gale, 2000). Unanticipated and sudden changes in defaults and adjustments of asset prices can then lead to systemic financial instability (Ackerman, 2017).

To better anticipate and avoid instability, "material" information regarding financial commitments must be examined. Information on an issuer is to be considered material if "a reasonable person would consider it [the information] important", according to the US Securities and Exchange Commission. Regarding the environmental issue, material information relates to environmentally-related impacts on asset issuers and to the likeliness for these impacts to translate into financial stress. The materiality of an information is here related to how economic costs from environmental shocks interact with financial commitments, financial fragility and expectations within the economy. As a general definition, an asset is to be considered exposed to environmental risks when it is issued by actors vulnerable to environmental impacts resulting in a situation of financial stress. An asset holder is to be considered exposed to environmental risks if the amount of its assets exposed to environmental risks is large enough to put him under financial stress.

For transition risks, the chain of event conducting to adverse financial consequences is as follows (Semieniuk et al., 2021). Drivers of transition shocks materialize, such as technological, political or preference changes. These events lead to economic costs within the economy (real vulnerability). Depending on financial holdings, the adaptation capacities of involved agents and changes in expectations, financial consequences ensue. The two main types of financial consequences are credit default and market devaluation. On the one hand, the loss of assets and income due to transition shocks increases the likelihood of default on debt (Dafermos and Nikolaidi, 2019). On the other, investors holding financial assets could suffer negative portfolio effects due to the revaluation of assets triggered by the transition process (Campiglio et al., 2019).

ii Attributes of EIO tables and balance sheets data for assessing the environmental exposure of financial assets

To identify assets exposed to environmental risks, it is required (i) to anticipate environmental shocks and their implied economic costs, and (ii) to assess the implications of those costs for existing assets, regarding financial commitments and resilience capacities of concerned actors. In that aim, it is thus needed to articulate indicators of real vulnerability with indicators of financial holdings and adaptation capacity. In an EIO-BS framework, while the EIO part is used to assess real vulnerability, BSs allow to identify holdings towards these activities as well as to assess the financial fragility of the units concerned.

Environmental impacts on the real economy incur specific shocks and indirect spillover effects within the industrial network, leading to real vulnerabilities. The first strength of EIO analysis for assessing environmental vulnerabilities is its ability to identify spillovers that occur through multiplier effects (Dietzenbacher and Velázquez, 2007; Rose and Wei, 2013; Koks and Thissen, 2016), input–output links being considered as propagation channels of demand or supply shocks (Acemoglu et al., 2012, 2015). The other material information provided directly by an EIO table concerns the origin of environmental shocks. Regarding transition risks, polluting agents can be considered as the primary targets for adverse changes in policy, preference or technology. Agents' footprint therefore indicates a potential vulnerability to transition shocks. In this respect, non (direct) polluters may be exposed to supply or demand shocks if polluters in their network are affected, or in other words, if their upstream or downstream contribution turns into a vulnerability. However, in the primary sense of environmental materiality, agents footprint (an impact *on* the environment) does not necessarily imply the vulnerability (to an impact *from* the environment). A comprehensive assessment requires further forward-looking efforts integrating political, technological and reputational aspects. The evaluation of discussed policy and technology shocks (Choi et al., 2010; Cooper et al., 2016) or recognized transition scenarios (Wiebe et al., 2018; Malerba and Wiebe, 2021) are strategies used in the EIO framework to overcome this shortcoming.

On the financial side, agents' BSs indicate financial dependencies prevailing between agents, and provide crucial information for assessing the possibility of liquidity and/or solvency risks. As Minsky (1967, p.47) puts it, "[t]he set of events that will lead to default depends upon the balance sheet structure of the firm at the time the event occurs". This is why the emphasis on balance sheets is so important in the study of financial crises (Allen et al., 2002; Kiyotaki and Moore, 1997; Bezemer, 2010; Tsujimura and Tsujimura, 2011; Kinsella, 2019). Material information include in this regard financial commitments, profitability indexes, and collateral values. From a balance sheet perspective, liabilities are understood as commitments to pay a certain amount in the future, which incurs a stream of expenses until that time (the service of external financing - interests or dividends); profitability is captured by the streams of incomes and expenses in a given period, measured for instance by the operating income before depreciation; and collaterals are identified in the assets side of the balance sheet. Combining these pieces of information helps evaluating financial stress through the computing of gearing or leverage ratios (Beaver, 1966; Altman and Hotchkiss, 1993; Sun et al., 2014). The exposition to risks is then assessed by linking debts to creditors, and by identifying agents concomitantly vulnerable to shocks and financially fragile. Balance-sheet network analysis of financial contagion can ultimately be conducted in order to capture second, third and fourth round effects throughout the financial system (Battiston et al., 2007; Barucca et al., 2020; Roncoroni et al., 2021).

The financial data required in a combined EIO-BS framework must describe either balance sheets at the industry level (see, for instance, European Central Bank (2015) or Stats SA (2019)), or assets in portfolios differentiated by industries (see, for instance, European Central Bank (2018) or Bureau Van Dijk Orbis database). The advantage of using industry-level balance sheet data is that it provides a complete picture of the financial balances within productive units. Industry-level balance sheet data are indeed meant to provide a comprehensive representation of industrial sectors' financial commitments and assets. Portfolio data are, for their part, commonly delineated to a specific set of asset holders and thus miss some financial commitments issued by firms despite they can be exposed to shocks (Godin and Hadji-Lazaro, 2022). However, two issues arise with industry-level balance sheet data. First, these data alone do not allow for the assessment of shocks' financial propagation. To assess financial propagation, one should also be able to link owners to issuers balance sheets (thanks to whom-to-whom portfolio or flow-of-funds data - Castrén and Kavonius (2009)). Second, it is companies, not industries, that raise funds. At the industry level, it is not clear how the market and financial structure of each sector can affect the financial implications of a shock (number of firms, disparities in leverage and profitability, degree of competition, government involvement...). Overcoming this limitation is, nevertheless, facilitated by the conformity of the EIO-BS framework with the National Accounts, making it possible to

	Identification of critical commitments	Measurement of shock-induced financial losses
Real vulnerability	footprint-based or broader prospective criteria	shock-induced economic performances
Financial vulnerability	financial holdings and fragility indicators	financial adjustment or macro-financial effects

Table 1: *Types of exposure assessments in a EIO-BS approach*

connect with data of other types and scales.

iii Methods to assess financial exposure in an EIO-BS framework

Two types of method can be followed in an EIO-BS framework to assess the environmental exposure of financial assets: the identification of environmentally critical commitments, and the measurement of financial losses induced by specified environmental shocks. Table 1 summarizes the main characteristics of the two strategies. On the one hand, critical commitments analysis identifies financial participations toward agents presumed as environmentally vulnerable according to real and financial criteria. Criteria to identify vulnerable activities can be footprint-based only or integrate a wider range of prospective arguments. Information to identify vulnerable financial assets may be limited to financial commitments only, but may also incorporate financial stress indices to account for the financial robustness of concerned agents. On the other hand, the measurement of shock-induced financial losses makes use of the EIO-BS framework as a macro stress-test tool in order to calculate the amount of financial depreciation implied by specified environmental shocks. Real vulnerability corresponds to economic performances determined either exogenously by environmental scenarios or endogenously in response to environmental shocks. Induced financial losses is then measured by combining economic performances to financial adjustment or macro-financial models.

Identification of critical commitments

Critical commitments are identified according to vulnerability criteria applied to issuing agents. For transition risks, the criteria can be the footprint of economic units, based on the belief that environmentally responsible agents will be the main losers of the transition. In this case, footprints and debt commitments are assessed among sectors and assets holders in order to identify financial dependencies to polluting agents. What matters is not so much the physical footprint embedded in a portfolio's assets as the share of the portfolio that is based on high-polluting sectors.[10] This kind of exploratory exercise leads to results such as those of Alogoskoufis et al. (2021) for instance, who show that around 30% of euro banks' equity and corporate bond portfolios consist of high-emitting Non-Financial Companies (see also Giuzio et al. (2019) or Schotten et al. (2016) for this type of assessment). To identify critical amounts of financial holdings in a more systematic way, one can also computes "footprint-based financial exposure indices", designed to identify units that simultaneously concentrate environmental responsibility and financial commitments relative to the rest of the economy. The exposure index of Monasterolo et al. (2017) for instance addresses "the question of how much is each financial actor exposed to climate risk through its portfolio, given the GHG emissions represented by its assets" (p.500). Carbon Intensity metrics of TCFD (2017)

[10] Unlike financial responsibility that is expressed in physical quantities, exposure must be addressed in monetary terms. Imagine, for instance, a firm with a large ecological footprint. Let's say that the company only needs a small monetary credit advance from a bank (the firm has only one type of liability). In this case, even though the footprint embedded in the bank's assets would be large (the bank holds the full financial responsibility for the polluter), the bank's monetary exposure to this entity could be very small relative to the rest of the assets it owns. In the end, although the bank has a large (physical) embedded footprint, it is not necessarily (financially) exposed to environmental risks.

are other examples of such footprint-based exposure indexes. And in the same vein, quantitative thresholds à la Faiella and Lavecchia (2020)'s notion of Carbon Critical Sector also helps identifying parts of the economy concentrating environmental footprint and financial commitments.

The advantages of these approaches are their simplicity and their independence from additional hypothesis or other data than EIO tables and BSs. However, their shortcomings are of at least two kinds. First, such assessments do not account for the deviation of vulnerability from environmental contribution. On the real side of the picture, although polluting agents are certainly the primary targets of transition shocks, their footprint does not precisely indicate a vulnerability to such shocks. With respect to technological risks, for example, it is clear that a high-emitting technology that is easily interchangeable with a low-emitting one is more vulnerable than a technology that is equally high-emitting but used for critical activities and difficult to replace. To address this shortcoming, a distinction have to be made between critical and non-critical sectors on the basis of prospective arguments that move well beyond the footprint criterion. Such a distinction can, for instance, be inspired from the list of "Climate Policy Relevant Sectors" (CPRS) constructed by Battiston et al. (2017) (see also the notion of "Carbon Related Asset" in TCFD (2017)). Such a list provides a granular classification of economic activities according to their exposure to transition risks, taking technological, industrial and political aspects into account. On the financial side, although the dependency to agents vulnerable to environmental shock is the first condition for financial risk to emerge, the financial fragility of concerned agents is also a necessary condition for it. Indeed, if a unit is financially healthy enough, it will be able to adapt to shocks. In addition to commitment levels, the computing of specific financial ratios (e.g., gearing ratios, Altman (1968)'s Z-score... etc) can be explored in an EIO-BS framework in order to refine financial criteria of vulnerability (Godin and Hadji-Lazaro, 2022).

Measurement of shock-induced financial losses

Nevertheless, even taking these new criteria into account, an important shortcoming of critical commitments analysis remains: only a one-shot picture of economic and financial situations are envisioned, from which no precise measure of financial consequences is drawn. What one might want to measure, however, is the precise financial effect of specific environmental shocks. This can be achieved in an "EIO-BS stress-test" approach combining environmental scenarios and financial valuation modules. Macro financial stress testing typically estimates the impact of shocks on economic variables first and then uses those variables as inputs into financial risk models. In an EIO-BS stress-test framework, the exposure of finance is precisely defined as the total amount of assets depreciation due to direct and indirect effects of the environmental scenario. The financial loss can be expressed as a level of asset devaluations or as an amount of non-performing loans, bonds or trade payables. For transition risks, these losses are induced by a specific transition path relative to a business-as-usual scenario.

In an EIO-BS framework used as a macro stress-test tool, one can derive the set of financial losses implied by an exogenous transition scenario in the following way. On the real side, the transition scenario is simulated based on the input-output structure of the economy. Following the Wiebe et al. (2018)'s method, the parts of the EIO system that must be changed exogenously are mainly the final demand components, the intermediate and factor input coefficients, and the environmental stressor matrix. Then, the simulation is performed by taking the previous year's table as an initial estimate for the current year and by adjusting some current year components to the scenario specifications. One finally obtains trajectories of production and value-added by industry. A simplified version in of the Wiebe et al. (2018)'s model formulated in a system of symmetric input–output tables is summarized by:[11]

$$\mathbf{x_{t,s}} = (I - A_{t,s})^{-1}\mathbf{y_{t,s}} \tag{2}$$

$$\mathbf{va_{t,s}} = \gamma_{\mathbf{t,s}}\mathbf{x_{t,s}} \tag{3}$$

where $\mathbf{va_{t,s}}$ is the vector of value added in year t in the scenario s, $\gamma_{\mathbf{t,s}}$ denotes the vector of value added per unit of output, $\mathbf{x_{t,s}}$ denotes the outputs of industries, $A_{t,s}$ denotes the direct requirements (or technical coefficient) matrix, and $\mathbf{y_{t,s}}$ denotes final demands. Direct requirements, final demands and value added per unit of output are exogenously determined based on current data, expert knowledge and the scenario's criteria.

Financial losses are then estimated by combining these economic trajectories to financial valuation adjustment models and balance sheet network analysis. The value-added vector can firstly be decomposed into a rectangular matrix including various components comprised in the IO table like wages payment, gross operating surplus and taxes. These components are then combined to financial information in order to build up indicators of economic and financial performances (including mainly profitability, market shares, and financial stress indicators). For instance, the coal sector might stop producing very quickly in the scenario and then stop generating cash flow. According to the stock of debts and shares issued by the corresponding companies, it is then up to the financial valuation module to calculate the implied loss (write-down) incurred by concerned assets.

First-round financial losses ($\Xi^{\mathbf{1st}}_{\mathbf{t,s}}$) represent the depreciation of the assets issued by the industries negatively impacted by the transition pathway. These losses result from the interaction of, on the one hand, economic performances derived from the value-added components and, on the other hand, financial commitments derived from BS data:

$$\Xi^{\mathbf{1st}}_{\mathbf{t,s}} = \mathbf{f^{1st}}(\mathbf{va_{t,s}}, \mathbf{m_{t,s}}, ...) \tag{4}$$

where the function $\mathbf{f^{1st}}$ derives first-round financial losses from the combination of, mainly, economic performances ($\mathbf{va_{t,s}}$) and financial commitments ($\mathbf{m_{t,s}}$). The precise module (or functional form) used can be inspired from various existing models (Monasterolo et al., 2018; Vermeulen et al., 2021; Allen et al., 2020). Monasterolo et al. (2018) and Roncoroni et al. (2021) for instance model first round effects (in their case, the change in the expected value of loans and obligations) by mainly addressing the effect of a change in profitability subsequent to a transition shock on the expected value of the debt instruments issued (assuming a linear relation between changes in profitability and changes in the expected value of these instruments). In a simplified form, it gives:

$$\Xi^{1st}_{t,TRANS,z,i} = \min\{0, m_{t,TRANS,z,i}.(1 - r_{t,z,i}).\chi_i.\frac{\vartheta_{t,TRANS,i} - \vartheta_{t,BAU,i}}{\vartheta_{t,BAU,i}}\}$$

where, $r_{t,z,i}$ is the recovery rate coefficient on the title z issued by the sector i, χ_i is the elasticity of profitability in respect to the market share of the sector, and $\vartheta_{t,TRANS,i}$ and $\vartheta_{t,BAU,i}$ are the market shares of industry i in, respectively, the transition ($TRANS$) and the business-as-usual (BAU) scenarios. Regarding a scenario s, the market share can be derived from values-added as follows:

$$\vartheta_{t,s,i} = \frac{va_{t,s,i}}{\sum_k va_{t,s,k}}$$

Second-rounds financial depreciation ($\Xi^{\mathbf{2nd}}_{\mathbf{t,s}}$) refers to direct financial contagion effects subse-

[11] Bold letters express vectors, upper case letters express matrices and normal lowercase letters express scalars.

quent to the first round losses (Battiston et al., 2017). It relates to the transmission of financial losses from a financial institution to another institution via a bilateral contract stipulating a financial obligation of one to the other (Roncoroni et al., 2021). Based on the work of Lawrence Klein and Richard Stone, Tsujimura and Mizoshita (2003) proposed a matrix formulation of assets and liabilities (the Asset-Liability matrices) derived from BS data that is suited for the study of such intrafinancial contagion. From the Asset-Liability matrices, Tsujimura and Tsujimura (2011) derive the D and B matrices taking as elements respectively the ratios of specific instruments in the asset sectors' portfolio and the ratios of specific instruments in the liability sectors' portfolio. Since the deterioration of the balance sheet of a financial institution has a negative impact on the value of its obligations held by its counterparties, the total loss made up by each sector is derived by combining D and B to the first-round financial losses as follows:

$$\Xi_{\mathbf{t,s}}^{\mathbf{2nd}} = P_t(I - D_{t,s}B_{t,s})^{-1}\Xi_{\mathbf{t,s}}^{\mathbf{1st}} \tag{5}$$

where the leakage flux matrix (P_t) specifies the share of the effect that is absorbed, or 'recovered', by each sectors (and then not propagating further in the financial network). This expression can be conceived as a matrix format generalization of more specific models such as Battiston et al. (2017)'s and Roncoroni et al. (2021)'s calculations of 2nd round effects. It reveals the consistency between the EIO and BS approaches, and thus their ability to be combined for the study of financial vulnerability.

Finally, strategies to capture third-rounds effects (fire-sales contagion among financial institutions, $\Xi_{\mathbf{t,s}}^{\mathbf{3rd}}$) and fourth-rounds effects (losses transferred to external creditors, $\Xi_{\mathbf{t,s}}^{\mathbf{4th}}$) have also been proposed (see Roncoroni et al., 2021). The sum of all effects gives the total depreciation ($\Xi_{\mathbf{t,s}}^{\mathbf{tot}}$) of financial assets induced by the transition path analyzed:

$$\Xi_{\mathbf{t,s}}^{\mathbf{tot}} = \Xi_{\mathbf{t,s}}^{\mathbf{1st}} + \Xi_{\mathbf{t,s}}^{\mathbf{2nd}} + \Xi_{\mathbf{t,s}}^{\mathbf{3rd}} + \Xi_{\mathbf{t,s}}^{\mathbf{4th}} \tag{6}$$

The above stress test method remains however static in the sense that no feedback mechanisms are permitted. To pursue a dynamic analysis, such an EIO-BS stress test module should be coupled to a wider macro-financial model, including a complete Financial Social Accounting Matrix as well as behavioral equations determining production and investment. Such a model could be based on an EIO-Stock-Flow-Consistent (SFC) structure (Godley and Lavoie, 2006), EIO-SFC models being the modeling pendant to the EIO-BS framework (see Berg et al. (2015) for example). In such a model, economic performances would endogenously react to exogenous environmental shocks and macroeconomic retro-actions, inducing financial losses and instability (see the IO-SFC model of Jackson and Jackson (2021) for instance). In this regard, Semieniuk et al. (2021) give worthy insights by developing a theoretical framework which captures the drivers, transmission channels, and impacts of the exit of carbon intensive industries on the financial system as well as on the feedback from the financial system into the rest of the economy. Studying these insights in a macro EIO-SFC framework is certainly a promising research avenue. The combination with an Integrated Assessment Model would also help adding biophysical shocks and environmental retro-actions (see the EIO-SFC model of King (2020) for instance).

iv Double-materiality: a bridge between responsibility and exposure

Although the assessments of financial responsibility and exposure have, at first sight, different purposes, both have in fact deep inter-relationships. Debt can be seen as an institutional tool, granting "virtual wealth" (Soddy, 1933), that humans use to moves energy and matter from the future to the present. But in order to pay back the debt, energy and matter must also be used

(Hagens, 2020). Here appears the essential relation between financial responsibility and financial exposure: finance enables production and environmental degradation, but that very unsustainable process negatively influences the production system's capacity to comply with debt obligations. This means that the impacts of investors on the external world is material to the impacts from the external world on the value of their assets. We have emphasized in this paper that an asset's footprint, while an important piece of information to evaluate transition risk, is not in itself a valid indicator of vulnerability. In fact, the information becomes fully material if one takes into account the implications of that footprint for the emergence of environmental shocks.

The concept of "double materiality", that have been recently used by the European Commission (2019), precisely encompasses both the "financial" materiality and the "social and environmental" materiality - the latter affecting the former (Kedward et al., 2020). Double materiality emphasizes the causal relation existing between the (physical) responsibility of finance and its (monetary) exposure. The notion stresses that the environmental vulnerability of a financial asset responds endogenously to its environmental contribution.

For physical risks, the value of a financial asset is affected by its environmental consequences because these consequences trigger the occurrence of physical shocks. The causality can be formulated thanks to pressure-impact relations, translating environmental footprints into socio-economic impacts (Steinmann et al., 2017), to be subsequently translated into economic and financial vulnerability.

For transition risks, the value of a financial asset is affected by its environmental consequences because these consequences modify both the transition path that the entire social metabolism must follow to reach environmental objectives and the alignment trajectory of the particular asset issuer in this path. The causality can be clarified through the notion of “carbon budget" (Friedlingstein et al., 2014, 2020; McGlade and Ekins, 2015), that can be generalized in the notion of “ecological budget".[12] The global ecological budget is defined as the level of footprint still allowed to the whole social metabolism in order to keep the level of environmental degradation below a certain level. Any increase in environmental degradation reduces the global budget. Once the global ecological budget is estimated, "local" ecological budgets for each units can be deduced from their current footprint and additional parameters regarding technological and political criteria. A local ecological budget represents the maximum amount of footprint that a unit can generate in order to comply with its role in the transition trajectory (Pfeiffer et al., 2016). Ecological budgets implicitly set limits to production and consumption, affecting the capacity to utilize physical assets, to earn revenues and hence to fill financial obligations.

The causal relation going from environmental responsibility to exposure to transition risks can be clarified in an EIO-BS framework as follows. In general terms, it means that the vector of financial losses in next period, $\mathbf{\Xi^{tot}_{t+1}}$, depends on environmental contributions in the current period, $\mathbf{ffp_t}$. The emergence of financial losses incurred by a specific asset is indeed conditioned by its level of footprint for two distinct reasons. First because the overall level of environmental degradation precipitates the transition path to be followed by the whole system in order to reach environmental objectives. Second, because the level of environmental degradation caused by a particular unit accentuates the relative mitigation efforts to be made by this unit in order to align itself to the transition path. For these two reasons, mitigation efforts are accentuated by environmental contributions, which amplify economic vulnerability and financial losses. The relation can be precised by emphasizing the role of ecological budgets in affecting economic trajectories and thus financial losses. In an illustrative purpose, we can express these relations as

[12] Despite it poses further problems when more complicated issues than climate, like biodiversity for instance, are considered, the ecological budget can be measured as of one can define some ecological objectives and measure current contributions.

follows:

$$\Xi^{\mathbf{tot}}_{\mathbf{t+1}} = \mathbf{f}(\mathbf{x_{t+1}} = \mathbf{f}(\mathbf{\Phi_t} = \mathbf{f}(\Phi_t = \mathbf{f}(\mathbf{ffp_t}, ...), ...), ...), ...) \tag{7}$$

where Φ_t is the scalar of global ecological budget (expressed in material units) which is conditioned by the current level of footprints and specified environmental objectives. $\mathbf{\Phi_t}$ is the vector of local ecological budgets given by the global ecological budget, political criteria and technical hypotheses retained for allocating mitigation efforts. Local ecological budgets then constraint output trajectories, which affect economic performances (see equation 3) and financial losses (see equations 4, 5 and 6) in next period.

By making it possible to study both the contribution of finance to environmental degradation and its vulnerability to environmental risks, the EIO-BS approach makes it possible to think about the interrelationships between both concerns, as highlighted by the concept of double-materiality. Article 29 of the French law on Energy and Climate adopts (implicitly) the concept of double-materiality. Indeed, the decree requires French financial institutions to disclose environmental risks *and* impacts. Disclosure musts include specific targets and measures of alignment with international goals and scenarios. The EIO-BS framework provides a macro-accounting tool that could help implementing and studying the implications of such a regulation.

V Case study

In an illustrative purpose, this section provides brief preliminary results derived from the EIO-BS framework. The case provides insights into the environmental responsibility and exposure of finance in France.

i Data

The EIO dataset we use is EXIOBASE v.3 (Stadler et al., 2018) (for the latest year available, 2011). The chosen footprint types for this case study are Greenhouse Gas (GHG) emissions (CC), Land use (LU), Raw Material use (MAT) and Water use (WT) (for the precise set of environmental stressors that are used, see Cabernard et al., 2019). Being the most commonly used, the chosen regime of attribution for real responsibility is the consumption-based principle (keep in mind that financial footprint could greatly change when looking at another regime of attribution).

The financial dataset we use is BACH (`https://www.bach.banque-france.fr/?lang=en`). It describes the size and composition of balance sheets by industry for twelves European countries and 84 sectors classified under the NACE rev.2 nomenclature. On the liability side of industries' balance sheets, height types of financing instruments are recorded:

- E: Equity
- $L1$: Bonds and similar obligations
- $L2$: Credit owed to credit institutions
- $L31$: Other credit owned by financial creditors
- $L32$: Other credit owned by non-financial creditors
- $L4$: Trade payables
- $L5$: Payments received on account for orders
- $L6$: Deferred liabilities

The two databases were combined according to a correspondence table (`https://github.com/BONSAMURAIS/correspondence_tables`).

ii Results

ii.1 Responsibility: The funding of GHG emissions in France

Regarding responsibility, the main output to be drawn from the EIO-BS framework is a picture of the financial instruments and holders that finance environmental footprints, as well as the value chains underlying the financial footprint embedded in these assets.

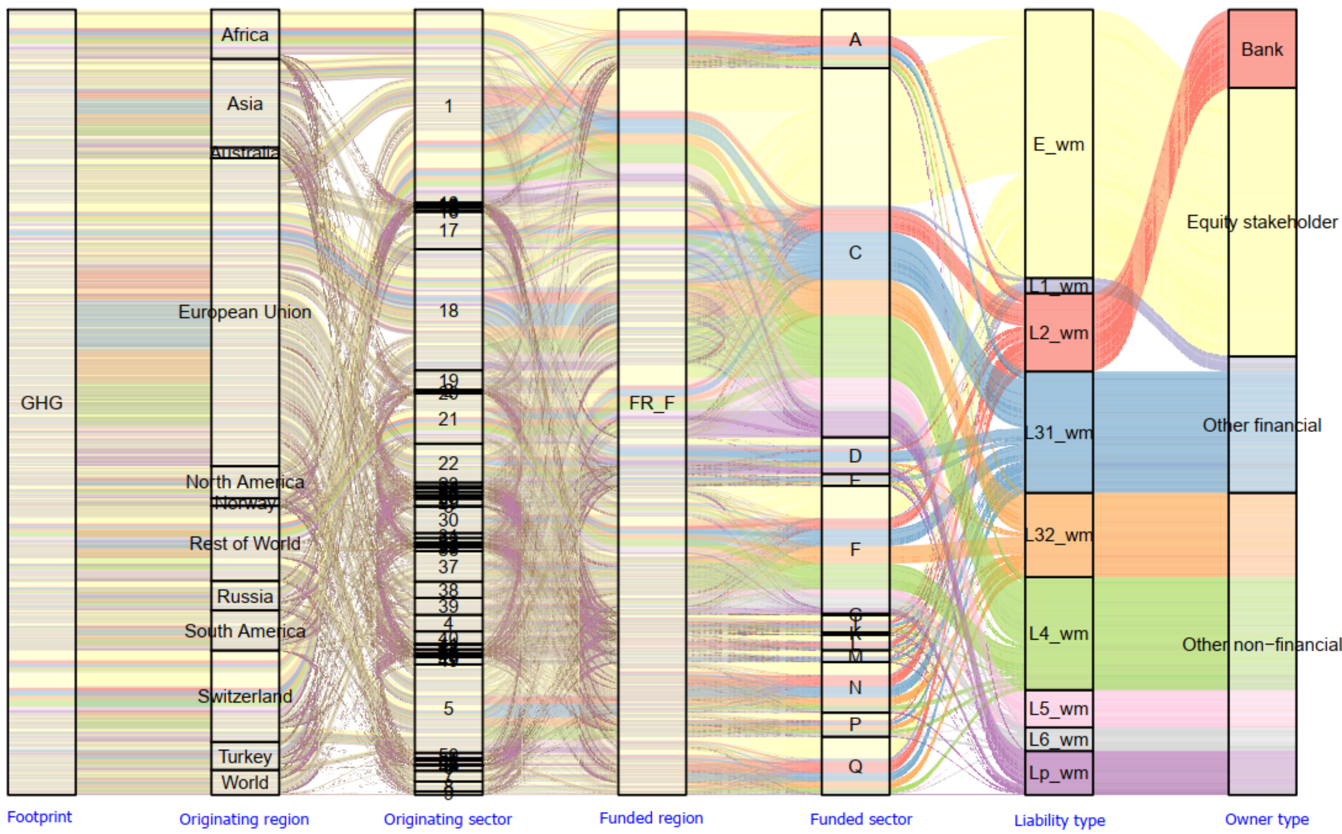

Figure 3: *Channels of real and financial environmental responsibility in France*

GHG emissions associated with French' final demand amount to 532 216 ktCO2eq. Figure 3 resumes in a Sankey diagram how the responsibility for this footprint is allocated among, from right to left, financial holders and instruments, funded sectors and countries, and sectors and regions where originates the footprint. While funded sectors are depicted by letters corresponding to the NACE rev.2 classification, originating sectors (in which originate the emissions) are depicted by numbers corresponding to EXIOBASE v.3 classification (see Table 2 and 3 in the Appendix). To assign financial responsibilities, the chosen financial attribution regime assumes no difference in the enabling capacity provided by each unit of monetary advance. In this case, the responsibility is simply shared among financial instruments according to their monetary share in units' funding structures.

As an example of results, we derive from this figure that approximately half of the footprint embedded in debts (non-equity) locates in assets owned by banks or by other financial institutions in the form of bonds and loans. The assets owned by banks are embedded with 58 791 ktCO2eq of

GHG emissions. 30% of GHG emissions embedded in bank loans occur in manufacturing sectors (included in C). 11% of GHG emissions embedded in bank loans are emitted by activities located in Asia.

ii.2 Exposure: The biophysical underpinnings of bank loans in France

On the vulnerability side, the results to be derived from an EIO-BS framework depict how financial instruments and holders are exposed to environmental shocks.

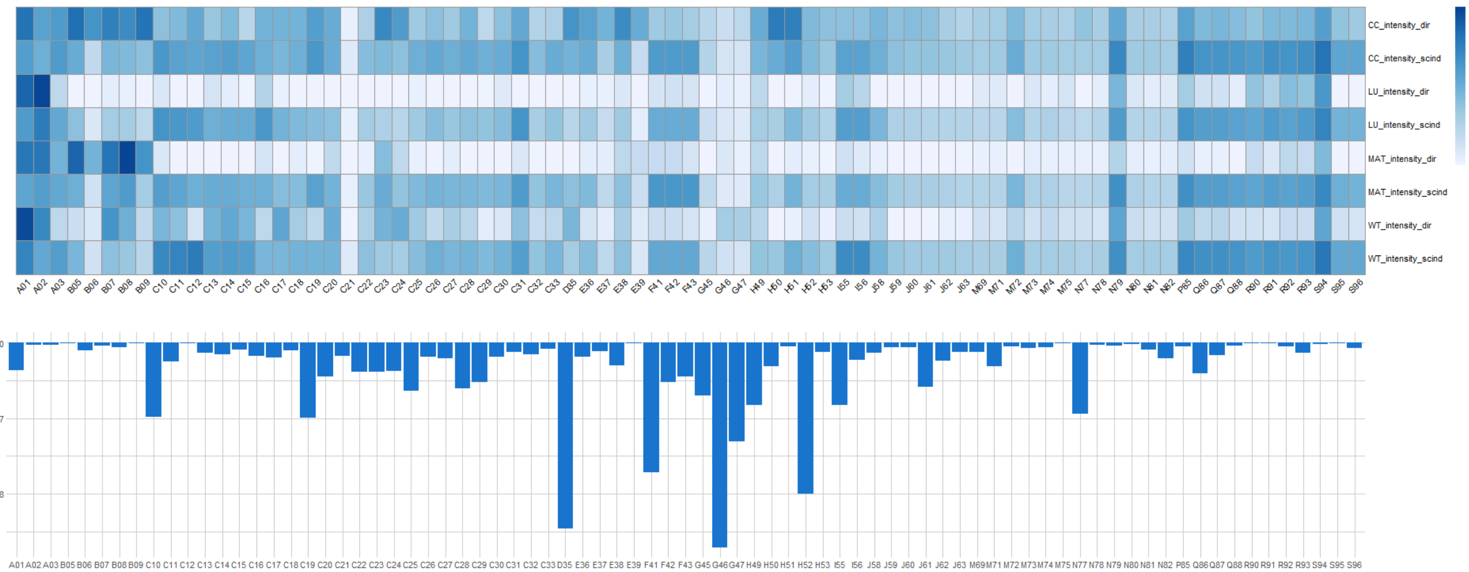

Figure 4: *Concomitances between footprint and debt intensities across industries in Europe*

As an example, a simple assessment of environmentally critical commitments highlights the sectors that are simultaneously highly indebted and highly polluting. The heatmap on the top of Figure 4 depicts the direct and indirect footprints intensity in production of *European* sectors for the four types of footprints analyzed (expressed in physical unity per unit of output).[13] The barplot on the bottom of Figure 4 depicts the absolute level of bank loans by sectors. The combination of both provides a first picture of how bank loans are based on the sectors the most concerned with the GHG-Land-Matter-Water nexus (Liu et al., 2015; Behrens et al., 2017; Font Vivanco et al., 2018). This dependency on biophysical factors indicates a potential exposure to transition risks.

For example, we can derive from this figure that the agricultural sector (A01), the utilities sector (D35), the coke and refined petroleum sector (C19) and the fabricated metal products sector (C25) are concomitantly heavily indebted in bank loans and directly intensive in several footprints. The corresponding amounts of loans are thus potentially exposed to direct transition shocks. Taking into account indirect footprints, it can be seen that the construction of buildings sector (F41), the land and pipelines transport sector (H49), the warehousing and support activities for transportation sector (H52), the accommodation sector (I55), the manufacture of food sector (C10) and the rental and leasing activities sector (N77) also emerge as simultaneously important loan issuers and footprint intensives. The corresponding amounts of loans are potentially exposed to

[13] Units for the different types of footprints were adjusted to make these intensities comparable, ranging from 0 to 10.

indirect supply transition shocks (think of the implementation of border-adjustment taxes, for instance, Kuik and Hofkes, 2010).

VI Conclusion

The paper presents how the environmental responsibility and exposure of financial assets can be assessed by combining EIO and BS approaches. The EIO-BS framework provides a relevant methodological foundation for defining and measuring financial responsibility through an integrated representation of environmental, industrial and financial relationships. Combined attributes of EIO and BS analysis also enable following environmental vulnerability propagating throughout industrial and financial systems. And as briefly considered with the concept of double-materiality, the EIO-BS framework also helps clarifying how the environmental contributions of financial assets participate to their vulnerability to environmental risks. The case study illustrated the applicability of the framework to available data. Its full potential remains however to be deployed through more extensive analysis and databases.

From a practical point of view, the EIO-BS framework may be of major interest to policymakers. The main contribution goes to the monetary and financial authorities willing to make the system they supervise aligned with environmental objectives and resilient to environmental risks. To help aligning the financial system, the EIO-BS framework allows monetary authorities to both qualify the "environmental content" of supervised assets (through the calculation of FFPs) and contemplate their underlying industrial network. Computing FFPs can first clarify the process of environmental disclosure (as a way to evaluate bonds' greenness for instance). Moreover, the environmental content of assets and the characteristics of their value chains are critical to calculate brown/green factors and to discriminate sustainable from unsustainable assets. These two abilities allow to go beyond disclosure by implementing the main tools proposed in the literature to influence credit allocation. Brown/green factors are needed to implement differentiated reserve/capital requirements (Rozenberg et al., 2013; Campiglio, 2016) or to differentiate target interest rates (van't Klooster and van Tilburg, 2020; Cahen-Fourot, 2021). The ability to discriminate between sustainable and unsustainable assets is required to tighten asset purchase programs - think of "green Quantitative Easing" (Schoenmaker, 2021; Dafermos et al., 2020a; Ferrari and Nispi Landi, 2021), or to implement direct guidance like credit control (Monnet, 2014; Bezemer et al., 2018). The EIO-BS framework also helps designing policies intending to mitigate environmental risks. Given their endogeneity (see the discussion on double-materiality) and under a precautionary approach (Chenet et al., 2021), policies that help mitigating the environmental contribution of financial systems (like those cited above) already participate to mitigate environmental risks (Dafermos and Nikolaidi, 2021). Nevertheless, independently from the contribution channel, the EIO framework also allow to identify critical commitments or financial losses induced from shocks propagating all over the industrial and financial network. In this way, the framework helps identifying assets to be put under supervision or even to be purchased by "bad banks" (Fischer and Baron, 2015; Spencer et al., 2017).

From a conceptual point of view, by allowing for the integration of socio-metabolic studies with macro-monetary analysis, the EIO-BS framework could constitute the empirical groundwork for a monetary theory of the social metabolism. The monetary circuit is embedded within social relationships, and in turn, the whole society is embedded within the natural environment (Fontana and Sawyer, 2016). A monetary theory of the social metabolism should make explicit the causal and co-evolutionary relationships between monetary and socio-metabolic regimes, i.e. how financial regimes influence metabolic regimes on the one hand, and how physical constraints play a decisive role in the interplay between financial regimes and metabolic regimes in the other hand. The development of an integrated conceptual, accounting, and modeling framework capable of capturing these relationships would represent a major achievement.

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Appendix

A	AGRICULTURE, FORESTRY AND FISHING
B	MINING AND QUARRYING
C	MANUFACTURING
D	ELECTRICITY, GAS, STEAM AND AIR CONDITIONING SUPPLY
E	WATER SUPPLY; SEWERAGE, WASTE MANAGEMENT AND REMEDIATION ACTIVITIES
F	CONSTRUCTION
G	WHOLESALE AND RETAIL TRADE; REPAIR OF MOTOR VEHICLES AND MOTORCYCLES
H	TRANSPORTATION AND STORAGE
I	ACCOMMODATION AND FOOD SERVICE ACTIVITIES
J	INFORMATION AND COMMUNICATION
K	FINANCIAL AND INSURANCE ACTIVITIES
L	REAL ESTATE ACTIVITIES
M	PROFESSIONAL, SCIENTIFIC AND TECHNICAL ACTIVITIES
N	ADMINISTRATIVE AND SUPPORT SERVICE ACTIVITIES
O	PUBLIC ADMINISTRATION AND DEFENCE; COMPULSORY SOCIAL SECURITY
P	EDUCATION
Q	HUMAN HEALTH AND SOCIAL WORK ACTIVITIES
R	ARTS, ENTERTAINMENT AND RECREATION
S	OTHER SERVICE ACTIVITIES
T	ACTIVITIES OF HOUSEHOLDS AS EMPLOYERS; UNDIFFERENTIATED GOODS
U	ACTIVITIES OF EXTRATERRITORIAL ORGANISATIONS AND BODIES

Table 2: *NACE rev.2 sector categories*

1	Cultivation of paddy rice
2	Cultivation of wheat
3	Cultivation of cereal grains nec
4	Cultivation of vegetables, fruit, nuts
5	Cultivation of oil seeds
6	Cultivation of sugar cane, sugar beet
7	Cultivation of plant-based fibers
8	Cultivation of crops nec
9	Cattle farming
10	Pigs farming
11	Poultry farming
12	Meat animals nec
13	Animal products nec
14	Raw milk
15	Wool, silk-worm cocoons
16	Manure treatment (conventional), storage and land application
17	Manure treatment (biogas), storage and land application
18	Forestry, logging and related service activities
19	Fishing, operating of fish hatcheries and fish farms; service activities incidental to fishing
20	Mining of coal and lignite; extraction of peat
21	Extraction of crude petroleum and services related to crude oil extraction, excluding surveying
22	Extraction of natural gas and services related to natural gas extraction, excluding surveying
23	Extraction, liquefaction, and regasification of other petroleum and gaseous materials
24	Mining of uranium and thorium ores
25	Mining of iron ores
26	Mining of copper ores and concentrates
27	Mining of nickel ores and concentrates
28	Mining of aluminium ores and concentrates
29	Mining of precious metal ores and concentrates
30	Mining of lead, zinc and tin ores and concentrates
31	Mining of other non-ferrous metal ores and concentrates
32	Quarrying of stone
33	Quarrying of sand and clay
34	Mining of chemical and fertilizer minerals, production of salt, other mining and quarrying nec
35	Processing of meat cattle
36	Processing of meat pigs
37	Processing of meat poultry
38	Production of meat products nec
39	Processing vegetable oils and fats
40	Processing of dairy products
41	Processed rice
42	Sugar refining
43	Processing of Food products nec
44	Manufacture of beverages
45	Manufacture of fish products
46	Manufacture of tobacco products
47	Manufacture of textiles
48	Manufacture of wearing apparel; dressing and dyeing of fur
49	Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear
50	Manufacture of wood and of products of wood and cork
51	Re-processing of secondary wood material into new wood material
52	Pulp
53	Re-processing of secondary paper into new pulp
54	Paper
55	Publishing, printing and reproduction of recorded media
56	Manufacture of coke oven products
57	Petroleum Refinery
58	Processing of nuclear fuel
59	Plastics, basic
60	Re-processing of secondary plastic into new plastic
61	N-fertiliser
62	P- and other fertiliser
63	Chemicals nec
64	Manufacture of rubber and plastic products
65	Manufacture of glass and glass products
66	Re-processing of secondary glass into new glass
67	Manufacture of ceramic goods
68	Manufacture of bricks, tiles and construction products, in baked clay
69	Manufacture of cement, lime and plaster
70	Re-processing of ash into clinker
71	Manufacture of other non-metallic mineral products nec
72	Manufacture of basic iron and steel and of ferro-alloys and first products thereof
73	Re-processing of secondary steel into new steel
74	Precious metals production
75	Re-processing of secondary precious metals into new precious metals
76	Aluminium production
77	Re-processing of secondary aluminium into new aluminium
78	Lead, zinc and tin production
79	Re-processing of secondary lead into new lead, zinc and tin
80	Copper production
81	Re-processing of secondary copper into new copper
82	Other non-ferrous metal production

Table 3: *Exiobase sector categories*

83	Re-processing of secondary other non-ferrous metals into new other non-ferrous metals
84	Casting of metals
85	Manufacture of fabricated metal products, except machinery and equipment
86	Manufacture of machinery and equipment nec
87	Manufacture of office machinery and computers
88	Manufacture of electrical machinery and apparatus nec
89	Manufacture of radio, television and communication equipment and apparatus
90	Manufacture of medical, precision and optical instruments, watches and clocks
91	Manufacture of motor vehicles, trailers and semi-trailers
92	Manufacture of other transport equipment
93	Manufacture of furniture; manufacturing nec
94	Recycling of waste and scrap
95	Recycling of bottles by direct reuse
96	Production of electricity by coal
97	Production of electricity by gas
98	Production of electricity by nuclear
99	Production of electricity by hydro
100	Production of electricity by wind
101	Production of electricity by petroleum and other oil derivatives
102	Production of electricity by biomass and waste
103	Production of electricity by solar photovoltaic
104	Production of electricity by solar thermal
105	Production of electricity by tide, wave, ocean
106	Production of electricity by Geothermal
107	Production of electricity nec
108	Transmission of electricity
109	Distribution and trade of electricity
110	Manufacture of gas; distribution of gaseous fuels through mains
111	Steam and hot water supply
112	Collection, purification and distribution of water
113	Construction
114	Re-processing of secondary construction material into aggregates
115	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries
116	Retail sale of automotive fuel
117	Wholesale trade and commission trade, except of motor vehicles and motorcycles
118	Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods
119	Hotels and restaurants
120	Transport via railways
121	Other land transport
122	Transport via pipelines
123	Sea and coastal water transport
124	Inland water transport
125	Air transport
126	Supporting and auxiliary transport activities; activities of travel agencies
127	Post and telecommunications
128	Financial intermediation, except insurance and pension funding
129	Insurance and pension funding, except compulsory social security
130	Activities auxiliary to financial intermediation
131	Real estate activities
132	Renting of machinery and equipment without operator and of personal and household goods
133	Computer and related activities
134	Research and development
135	Other business activities
136	Public administration and defence; compulsory social security
137	Education
138	Health and social work
139	Incineration of waste: Food
140	Incineration of waste: Paper
141	Incineration of waste: Plastic
142	Incineration of waste: Metals and Inert materials
143	Incineration of waste: Textiles
144	Incineration of waste: Wood
145	Incineration of waste: Oil/Hazardous waste
146	Biogasification of food waste, incl. land application
147	Biogasification of paper, incl. land application
148	Biogasification of sewage slugde, incl. land application
149	Composting of food waste, incl. land application
150	Composting of paper and wood, incl. land application
151	Waste water treatment, food
152	Waste water treatment, other
153	Landfill of waste: Food
154	Landfill of waste: Paper
155	Landfill of waste: Plastic
156	Landfill of waste: Inert/metal/hazardous
157	Landfill of waste: Textiles
158	Landfill of waste: Wood
159	Activities of membership organisation nec
160	Recreational, cultural and sporting activities
161	Other service activities
162	Private households with employed persons
163	Extra-territorial organizations and bodies

Table 4: *Exiobase sector categories, continuation*