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European banks face significant vulnerability to ecosystem degradation and climate change

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The economy and the financial system, through its exposures to companies, have a dual relationship with nature. They do not only depend on it, but they can also affect it and be affected. This can give rise to nature-related risks, driven by the nature degradation, encompassing the loss of biodiversity and ecosystem services. We demonstrate how the economy and banks in the euro area are critically dependent on ecosystem services and how they simultaneously contribute to biodiversity loss through their biodiversity footprint. In our sample, 72% of the analysed companies in the euro area exhibit a high dependency on at least one ecosystem service. Out of the 2500 banks analyzed, 100 are responsible, through their loans to companies, for 87% of the total biodiversity footprint of the euro area banking system. Degradation of ecosystems and biodiversity loss can pose risks to the financial system by affecting companies' production processes and, consequently, impairing their ability to repay debt. Such nature-related risks can be exacerbated by climate change. Our analysis reveals that nearly 60% of loans in the euro area are exposed to companies facing unmet flood protection needs, highlighting the compound financial risks from multiple, interacting ecosystem and climate hazards.

A healthy nature is essential to sustain human well-being as well as to deliver a multitude of benefits to society through ecosystem services (ES)[1]. However, humanity has collectively failed to engage with nature sustainably. In the last decades, sharp increases in economic and population growth have enhanced pressures leading to biodiversity loss and ecosystem degradation[1,2]. Such trends put at risk the capacity of ecosystems to supply the services we depend on[2,3].

Economic sectors can be directly and/or indirectly dependent on ecosystems (e.g., through their supply chains). Agriculture, forestry and fisheries, construction, heat generation and electricity supply are the economic sectors with the highest direct dependencies on ecosystems[4]. For example, the agricultural sector exhibits high dependency on regulating and provisioning ecosystem services such as pollination, soil fertility, and surface water availability. The construction sector, by contrast, depends on the provisioning of natural resources, including the extraction of timber, minerals, and other raw materials. More than half of world's total GDP is moderately or highly dependent on ES and therefore at risk due to the current trends of biodiversity loss and ecosystem degradation[4,5]. The loss of six ES under different scenarios could lead, globally, up to €2.7 trillion in the real GDP lost by 2030 and up to €9.8 trillion lost by 2050[6].

By granting loans, banks play a crucial role in enabling companies to manage operations and fostering overall economic development. Banks therefore have a similar (though indirect) relationship with nature. Its degradation can disrupt companies' production reducing their profits and impairing their creditworthiness and solvency level. As a consequence, banks may face losses in their trading and loan books. Through their trading and lending activities, however, banks can support economic sectors that affect the state of ecosystems and biodiversity, potentially exacerbating nature degradation[7]. *De Nederlandsche Bank* found that 36% of their financial institutions' portfolios are highly dependent on ES, while at the same time they contributed €79 billion (in 2019) to finance companies involved in environmental controversies worldwide[8]. *Banque de France* found that 42% of their securities, in terms of value held by French financial institutions, are issued by companies that are highly dependent on at least one ES; while, the terrestrial biodiversity footprint associated with these securities was found to be at least 13 million hectares of pristine nature[9].

In addition, economic sectors and banks are also exposed to climate-related risks[10]. The loss of ES and climate hazards can compound, amplifying negative impacts on the economy and financial stability. Climate change and ecosystem degradation are closely interconnected. Climate hazards, such as drought and heatwaves, degrade ecosystems, while healthy

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ecosystems mitigate climate impacts by sequestering carbon and buffering against disturbances[11,12]. Understanding these compound effects is crucial for integrated risk management, economic resilience, and fostering a sustainable relationship between nature and society[5,13].

It is important to assess the euro area economy and the banks that finance it against two complementary dimensions of nature related financial risk. First, the dependency of companies on ES represents a direct proxy for physical risks arising from potential service disruptions. Second, the biodiversity impacts of financed activities serve as an indicator of transition risks stemming from evolving regulations, market shifts and reputational pressures.

First, we quantify the dependency of the euro area economy on ES by measuring how strongly companies rely on a range of services, based on the ENCORE (Exploring Natural Capital Opportunities, Risks and Exposure) dataset[14]. Examples include food and fiber (provisioning services), storm and flood protection, climate regulation, and freshwater provision (regulating services). A complete list of ecosystem services included in the analysis is provided in Supplementary Fig. 1.

Second, we assess the environmental pressures exerted by euro area companies and banks by estimating the extent of pristine natural habitats degraded through their activities. This analysis helps to quantify the biodiversity related impacts and spatial footprints associated with economic sectors and banks. This evidence is derived from the high granularity of the financial data on banks' loans granted to more than 4.2 million companies in Europe, with the total loan portfolio amounting to €4.3 trillion.

In addition, we highlight the importance of the compound effects of climate change and ecosystem degradation on financial stability. Although these risks are often analyzed in isolation, their interactions can lead to nonlinear, cascading impacts on economic output and the financial system. Our analysis explicitly identifies these compound risks, underscoring the need for integrated risk assessment and management frameworks. Addressing this climate-nature nexus is a critical step toward more realistic estimations of systemic risk for the economy and financial institutions and toward informing policy agendas that better align climate mitigation with nature preservation objectives[15].

Results

Dependency of euro area economy and banks on ecosystem services

The total dependency of economic activities (direct and indirect) on 21 different ES varies substantially across different economic sectors (Fig. 1a). Energy production, agriculture, forestry, and fishing exhibit the highest dependency, followed by manufacturing, transportation and storage, mining and quarrying, and real estate activities. Business and administration-oriented activities, such as public administration and financial activities, display a lower but still notable dependency. An estimated 72% of EA companies, equivalent to nearly 3 million entities, demonstrate a high level of dependence on at least one ES. In the event of ecosystem degradation, the dependent production processes would face critical disruptions, directly imperiling the financial viability of these companies.

Companies in EA strongly rely on several ES (Fig. 1b). Water provision from surface and ground water resources appear as the most relevant ES, especially for agricultural, manufacturing and energy production. Mass stabilization and erosion control, flood and storm protection and climate regulation are among the most important ES for companies in EA; these are provided mainly by the vegetation cover, protecting and stabilizing terrestrial, coastal and marine ecosystems. These services are essential for protection of economic activities against climate hazards such as floods and heatwaves.

Even though the major share of the total dependency of EA economy comes from the locations where companies are operating, an important share is attributed to indirect dependencies across the supply chain (Fig. 1b). To assess this dynamics, we use an environmentally extended multi-regional input-output (EE-MRIO) database, which allows us to determine country's dependence on ES outside the EA (Section Dependency of economic sectors on ecosystem services). This supply chain dependency reflects the contribution of companies outside the EA, operating across various sectors, whose outputs are exported to the EA. These companies are mostly dependent on ES in North America and Asia through their global supply chains (Fig. 1b).

The dependency of banks on ES, with respect to their corporate loan portfolios, is calculated as the exposure-weighted average of the ES dependencies of the companies to which the banks lend. This is determined using detailed data from AnaCredit, the EA credit register which provides granular insights into banks' corporate loan portfolios (Section Dependency of economic sectors on ecosystem services). These results are, then, aggregated at country and sector level. Banks in France, Germany, Italy, and Spain granted substantially larger volumes of loans compared to those in the rest of the EA. The highest share of banks' loans is granted to companies operating in manufacturing, wholesale and retail trade, and real estate sectors (Fig. 1c), which cumulatively represent 53% of all the loans here analysed. The highest dependency of banks' loans is on the provision of surface and ground water, and mass stabilisation and erosion control (Fig. 1c), mirroring the broader dependency seen in the EA economy. Overall, an estimated 75% of loans granted to EA companies, equivalent to nearly €3.2 trillion, demonstrate a high level of dependence on at least one ES.

Impact of euro area economy and banks on biodiversity

While EA companies have a remarkable dependence on ES, they also have direct impact on global biodiversity as well as indirect impacts through the supply chain. These impacts are measured by the biodiversity footprint. Here, the focus is on terrestrial biodiversity and two associated pressures from economic activities: land use and climate change. The biodiversity footprint is estimated for the year 2021. This year is chosen as it marks a phase of global economic recovery following the COVID-19 pandemic. As production and consumption rebounded, 2021 provides a representative snapshot of resumed economic activity and its environmental implications.

The biodiversity footprint is estimated to be equivalent to the loss of more than 580 million hectares of pristine habitats globally, roughly corresponding to 60% of the European land area. This measure integrates the loss of biodiversity as a consequence of the already observed land conversion and the potential biodiversity loss in the next 100 years (consistent with the IPCC recommendation) due to global warming induced by greenhouse gases (GHG) emissions[16].

The biggest impact is observed in the EA, where the economic activities actually take place (Fig. 2a). However, to fully understand the footprint of the EA economy, it is essential to adopt a global perspective. This is because many of the goods and services consumed in the EA rely on resources, labor, and land use outside its borders. The EA economy is responsible for substantial impacts also in other continents through the supply chain dependency. Relatively high impacts exerted in Asia and Africa can be attributed to high dependency on supply of agricultural, mining and manufacturing products from these continents. Increasing demand for agricultural outputs has driven rapid land conversion in these regions, causing habitat loss and fragmentation[17].

Overall, the sectors financed by EA banks that have the greatest impact on biodiversity are manufacturing, agriculture, and electricity production (Fig. 2b). Manufacturing causes impacts on biodiversity both through climate change and land use, while the production of electricity almost entirely through climate change. Almost the entire biodiversity footprint from financed activities in agriculture, forestry and fishing results from land use; only around 15% comes from climate change (Fig. 2b). Banks in France, Germany, Italy and Spain finance the biggest share of activities contributing to the total biodiversity footprint.

The contribution of financed activities to the total biodiversity footprint coming from climate change is slightly bigger than the one linked to land use, which comes especially on account of the strongest manufacturing sector. However, the financed impact in the rest of the world (through supply chain) can be equally attributed to both. Higher relative contribution

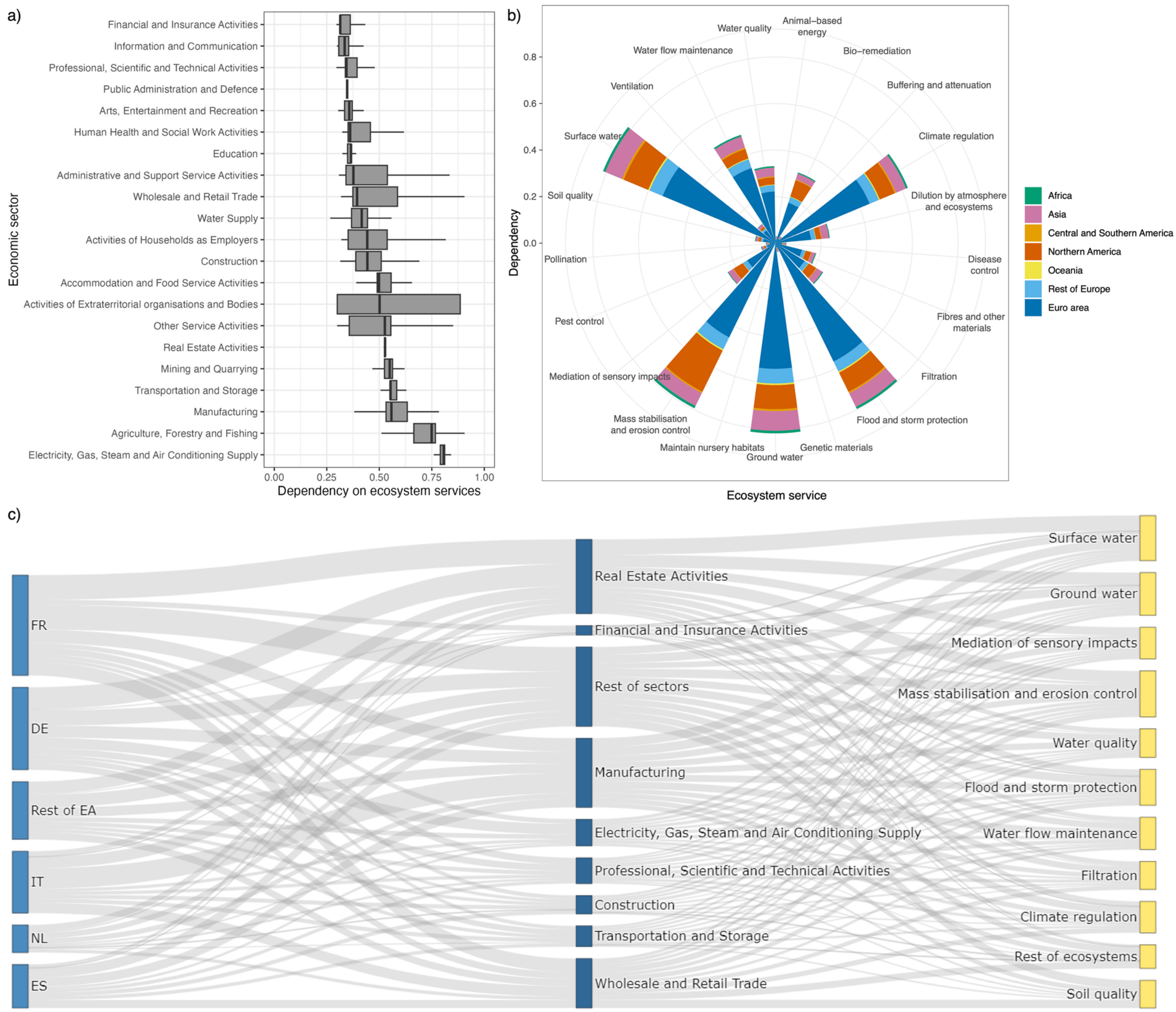

Fig. 1 | Dependency of euro area companies and banks providing loans on ecosystem services. **a** Total dependency of 21 main economic sectors in the euro area on ecosystem services. Total dependency integrates direct and indirect components. **b** Direct and indirect dependencies (indicated by different continents/regions) of companies on 21 different ecosystem services. **c** Country-level cross-sectoral disaggregation of banks' loans granted to companies operating in different sectors with varying dependency.

of land use at global level is a consequence of importing agricultural and forestry products (Fig. 2b).

The relationship between banks' impacts on biodiversity and the number of banks providing loans is highly nonlinear. The 10 largest banks (in terms of their biodiversity footprint), out of the 2500 here analysed, finance nearly 40% of the total biodiversity footprint (Fig. 2c). The cumulative impact increases to nearly 87% by considering the first 100 banks.

Exposure of EA companies and banks to climate and nature risk drivers

EA economic activities are, on one hand, highly dependent on ES and, on the other hand, they exert substantial impacts on biodiversity. This relationship poses high risk to the EA economy and banks, as loss of biodiversity has negative consequences for ecosystem functioning and ES supply[18,19]. But such intricate relationship can be made even more complex and fragile if we consider that other sources of risk exist, that can amplify the nonlinear mechanisms and processes linking ES and economics. For example, the loss of flood protection can amplify the impacts of extreme rainfall events driven by climate change. Thus, to avoid an underestimation of risks for the economy and the financial system, an integrated risk assessment approach is needed.

By combining the dependency on ES with climate physical risk drivers from the economy-wide climate stress test[10], we assess the exposure of EA companies and banks to compound climate and nature risk drivers. The considered climate hazards are: floods, droughts, heat stress, sea level rise, and wildfires. The corresponding climate physical risk scores integrate information on changing probability of these hazards to which companies would be exposed in the mid-century (following the RCP8.5 scenario).

Flood and drought risks for companies are assessed together with their dependency on the two related ES, flood protection and surface water provision, respectively. The dependency on the two ES is highly heterogeneous across sectors, whereas the climate risk scores appear more heterogeneous across different European regions (Fig. 3a, c). Agriculture, electricity supply, transport and storage sectors show higher dependency on flood protection and surface water provision than other sectors; the majority of economic sectors are, however, highly dependent on surface water provision (Fig. 3c). Companies in central and northern Europe are substantially exposed to flood risk (Fig. 3a); the opposite,

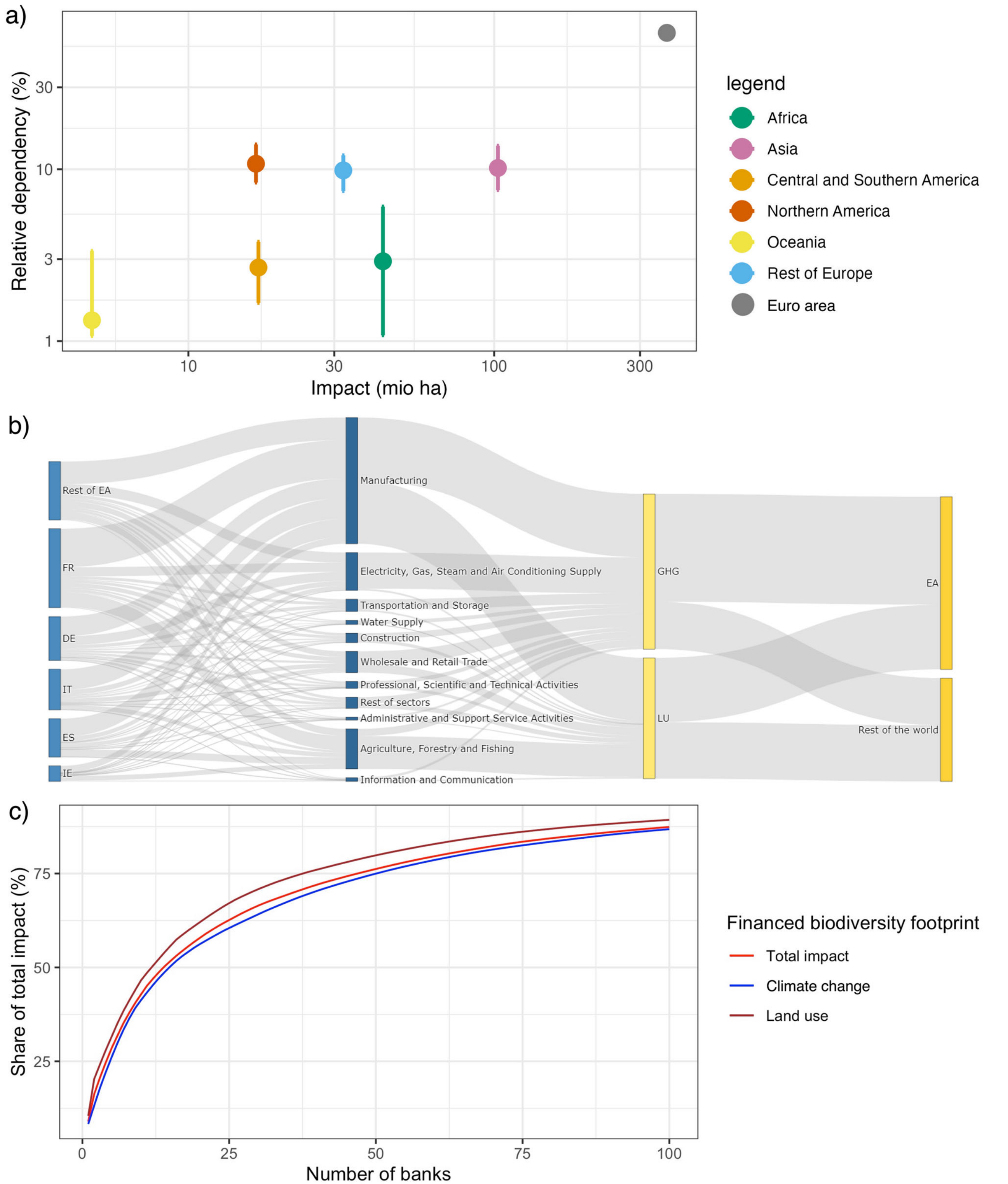

Fig. 2 | Biodiversity footprint of euro area economy and banks. a Relative dependency on ecosystem services in different continents/regions for euro area economy (y axis) and biodiversity footprint (x axis) of economic activities in these regions. The vertical bars indicate the range between dependency on least and most important ecosystem services, while the position of the dot indicates average dependency across different ecosystem service. **b** Financial flows (banks loans) in different euro area countries to companies operating in different economic sectors. The biodiversity footprint of financed economic activities is distinguished between two pressures: climate change and land use. **c** Cumulative share of total biodiversity impact attributable to the 100 most impactful euro area banks, expressed as a percentage of the combined impact of all banks in the study.

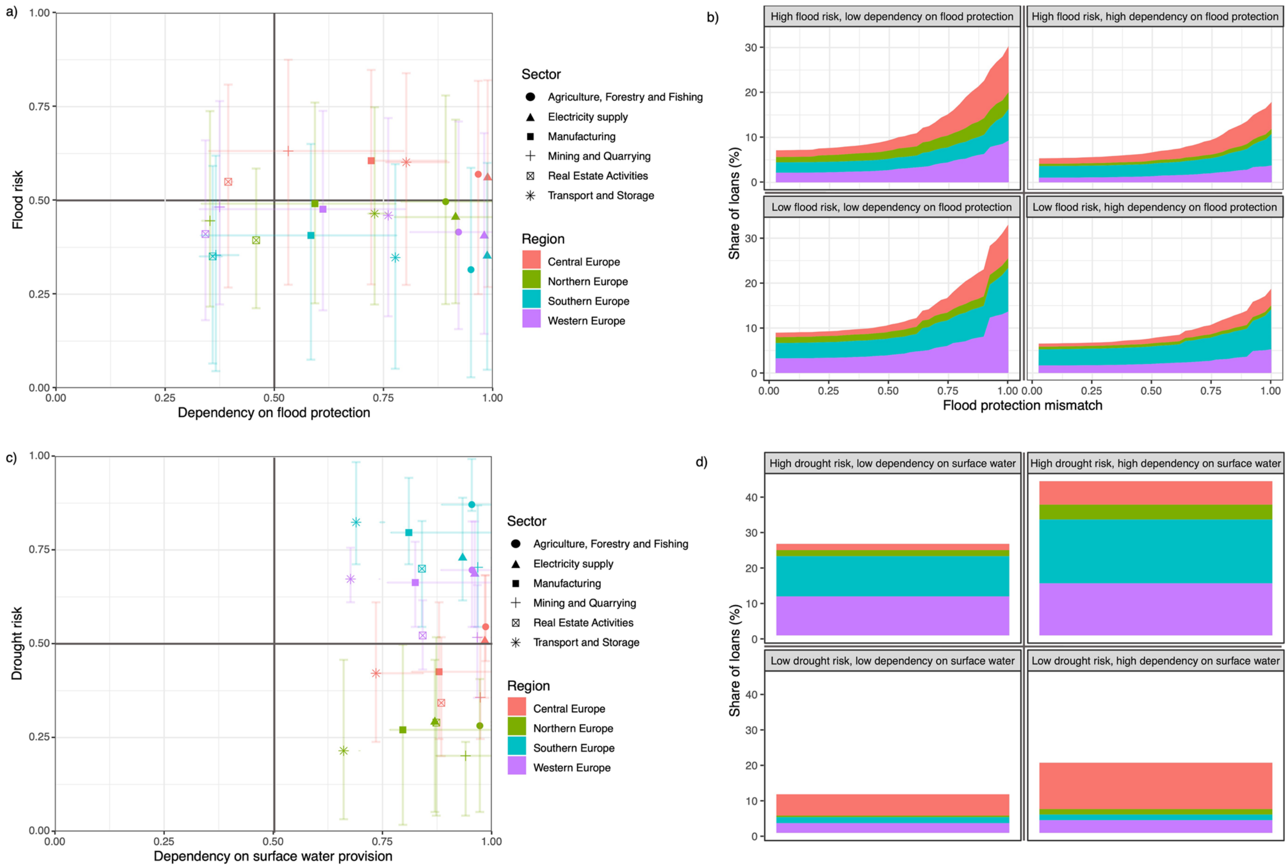

Fig. 3 | Exposure of the euro area companies and banks to climate hazards and ecosystem services. **a** Exposure of euro area companies to flood risk and their dependency on flood protection ecosystem service for different European regions. The horizontal (vertical) lines represent the inter-quartile range of dependency of companies on flood protection (inter-quartile range of exposure to floods in 2040s). Flood risk score takes values between 0 (not exposed to floods) and 1 (highly exposed to flooding). **b** Share of the total loan portfolio given to companies with different levels of flood exposure in 2040s and dependency on flood protection. Four different combinations of flood exposure and flood protection are distinguished, corresponding to their position in different quadrants in (**a**). Cumulative share of loans given to companies in different European regions is shown as a function of flood protection mismatch (i.e. unmet demand). The flood mismatch ranges from 0 (entire demand for ecosystem service is met) to 1 (there is no ecosystem service able to cover the demand). **c** Exposure of euro area companies to drought risk in 2040s and their dependency on surface water provision for different European regions. Drought risk score takes values between 0 (not exposed to droughts) and 1 (highly exposed to droughts). **d** Share of the total loan portfolio given to companies belonging to different levels of drought exposure in 2040s and dependency on surface water provision, corresponding to their position in different quadrants in **c**).

instead, holds true for drought, with companies in southern and western Europe showing stronger exposure.

Compound shocks from climate and nature risk drivers can materialize especially in economic sectors that are highly exposed to increasing climate hazards (e.g. associated with flood) and are, at the same time, also strongly dependent on related ES (e.g. to provide flood protection). For instance, when ecosystem degradation leads to decrease in flood protection, affected companies may experience amplified effects of flooding events. Similar consideration can be drawn for production processes that are highly dependent on surface water provision and exposed to increased drought risk (Fig. 3c).

From a systemic perspective, banks, via their corporate loan portfolio, are thus exposed to the compound risk arising directly from climate factors as well as loss of ES that are essential to sustain the production processes of companies. This risk increases as a function of mismatch between ES potential (the ability of ES to generate a service) and ES demand (the amount of service that is required by an economic activity)[20]. In the case of flood protection, the mismatch is defined as an unmet demand (i.e. ecosystems do not provide sufficient flood protection that is needed to protect socio-economic activities). The higher the mismatch, the lower the asset value protected by the ES.

In the case of flood, overall, more than 60% of the loans are granted to companies located in areas where more than half of flood protection demand is unmet (Fig. 3b). The share of the loan portfolio given to companies that are strongly exposed to increased flood risk and dependent on flood protection is the highest in central and southern Europe. More than 15% of entire EA loan portfolio is given to these companies, and more than half of these loans are exposed to high flood protection mismatch. Concerning drought, the highest share of the total banks' loan portfolio (more than 40%) is granted to companies highly exposed to this hazard and highly dependent on surface water provision. More than three quarters of this share belongs to companies in southern and western Europe (Fig. 3d).

To identify the complex channels through which the compound effects of climate and nature risk drivers influence EA companies, we perform a network analysis based on climate risk scores for mid-century (under the RCP8.5 scenario) as well as on ES dependency (Fig. 4). Physical risk scores for five climate hazards and 21 ES dependencies (Supplementary Fig. 1) are combined at company level to determine the strength of network connections, characterizing the likelihood of two different drivers compounding (Section Climate-nature nexus and network analysis).

Two distinct communities appear in the resulting network (Fig. 4). The first community contains climate hazards and a few of the most relevant ES from the dependency analysis: mass stabilization and soil erosion control, surface and ground water provision, bio-remediation and sensory impacts. The nodes of the first community are more strongly connected that the ones from the second community, which contains the

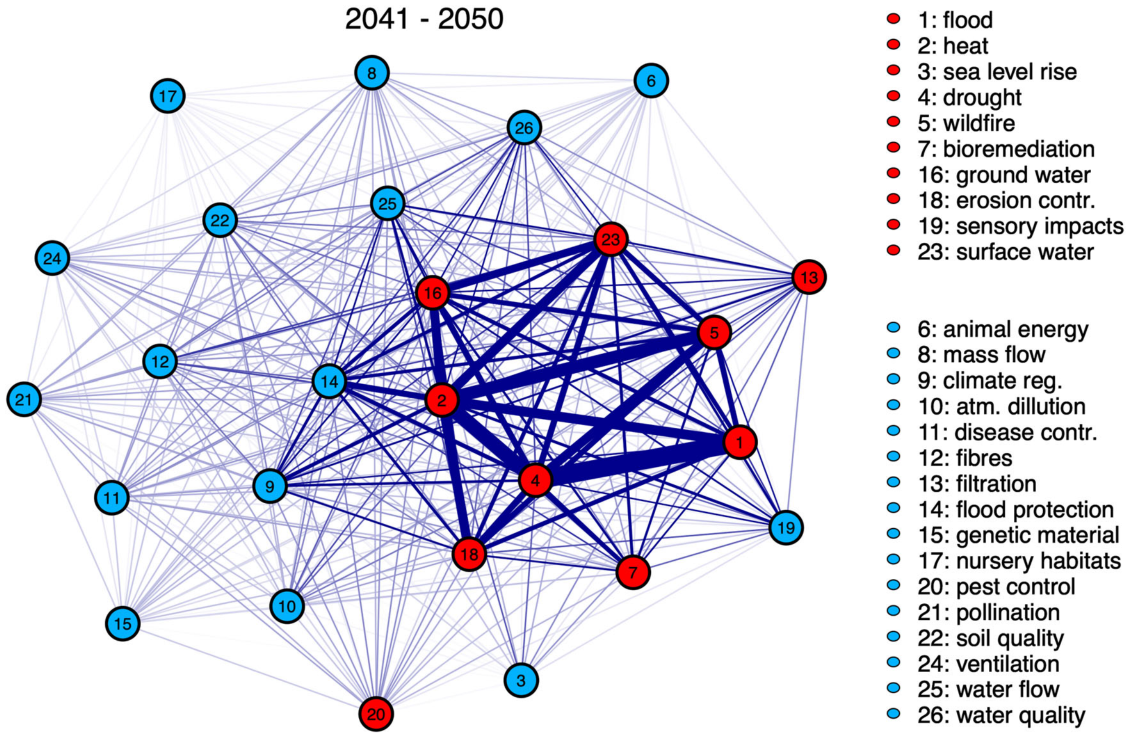

Fig. 4 | Typology of euro area companies in nature-climate space. The network diagram displays two distinctive communities and the connections between different nodes (climate hazards and dependencies on ecosystem services). The width of connections between two nodes is proportional to the exposures to climate hazards and dependencies on ES for each company, thus representing the potential for compound climate-nature shock amplification. The network diagram reflects the strength of connections in 2041-2050 (under the RCP8.5 climate scenario).

rest of the ES. Consequently, two types of potential risk amplification mechanisms can be distinguished from this network. The first one relates to compounding of two different climate hazards (such as drought and heat stress). The second type relates to compounding effect of climate hazard and ES loss.

The two distinct communities are strongly connected through ES such as flood protection, climate regulation, filtration, water flow maintenance, water quality and fibres provision. Each of these connections represents a potential channel for compound risk amplification (in case ecosystems are not capable of meeting the demand for their services) or increasing the resilience (in case healthy ecosystems are able to meet the demand for their services). Since ecosystems absorb roughly half of the anthropogenic CO_2 emissions[21], the connections with climate regulation (i.e. the capability of ecosystems to uptake and store the atmospheric carbon) represent the most relevant channels for amplification of transition risk for companies and banks.

The highest risk for EA companies and banks will likely be materialized through compounding effect of different climate hazards, mostly droughts and floods, droughts and heat waves, and wildfires and heatwaves (Fig. 4). Another prominent feature is drought compounding with reduced ground and surface water provision. In the latter case, healthy ecosystems can mitigate the negative influence of droughts, while degraded ecosystems can considerably worsen production processes for companies strongly depending on water.

Connections with some of the ES, such as nursery habitats, are less pronounced, however this likely reflects the fact that in our network analysis we were not able to account for the interdependences within the ecosystems necessary for their proper functioning and thus ES delivery.

Discussion

The aggregated EA banking sector shows a higher dependency on ES than the individual Dutch[8] and French[9] systems, while all three studies consistently underscore the critical role of surface and groundwater, flood and storm protection, climate regulation and soil erosion. While the dependency on certain ES such as pollination and nursery habitat maintenance may be relatively low, this should not diminish their relevance for both the economic and the banking system. These services are pivotal for maintaining ecosystem stability, which, in turn, supports the provision of other essential services[18,22]. The proportion of the total loan portfolio with a high level of dependency on these ES is relatively modest, resulting in lower scores.

European demand for ecological goods and services strongly exceeds the supply capacity of its ecosystems to produce biological products and absorb carbon emissions[23]. Unfortunately, economic activities that depend on these ecosystems are often among the main contributors to environmental pressures and diminishing the ecosystems' ability to provide essential services. The biodiversity footprint of companies is primarily concentrated within the EA countries. Nevertheless, our analysis reveals that this footprint extends far beyond the EA borders. This has crucial implications for global nature conservation and restoration initiatives, as established in the Kunming-Montreal Global Biodiversity Framework[24]. The potential repercussions of loans, therefore, can have profound and far-reaching effects on regions of key global significance for carbon storage and biodiversity[25].

The identification of loans granted to economic activities that exert substantial pressure on ecosystems represents an initial and pivotal phase in the adoption of nature-aligned economic policies. Similar to climate change mitigation, a faster and more efficient transition of economic and financial activities is imperative to minimize the future physical risk coming from ecosystem losses. The short-term costs of a timely and ambitious transition are more than offset by long-term benefits of limiting climate change[26] and nature degradation impacts.

In the financial sector, climate change and nature degradation are typically addressed as separate concerns. While climate and nature risks exhibit distinct characteristics (including varying time horizons, hazard inter-dependencies and spatial properties), they are intricately interconnected and have the potential to reinforce each other[27]. Policy actions taken to address climate mitigation will likely have an impact on biodiversity and ES, and vice-versa. For example, inadequately planned initiatives aiming at reforestation (e.g. monoculture) can have detrimental consequences on ecosystem health and its capacity to provide essential services, which are integral to economic stability and the banking sector. Conversely, climate mitigation policies can foster biosphere integrity by implementing the Kunming-Montreal Global Biodiversity Framework[24,28], thus improving ecosystem functioning both as a means of mitigation and adaptation to climate change. To minimize future risks for banks and ensure financial stability, it is imperative that nature restoration and conservation efforts are undertaken in synergy with climate mitigation and adaptation endeavors[29].

The highest risk for EA companies and banks will likely be materialized through compounding effect of different climate hazards and degradation of ecosystems that are crucial to protect companies and their economic activities against natural hazards and provide them with various natural goods. Better understanding of the dependence structure between climate and nature risks, that can amplify the overall impact on companies and banks, is required to avoid possible blind spots and risk underestimation[30,31]. This enhanced understanding is also essential to uncover innovative investment and market solutions, minimizing the transition and physical risks for the financial sector[32]. For instance, integrating the carbon offset provided by wild animals into the existing carbon credit markets could potentially address the financial gap in both biodiversity conservation and climate action[33]. The necessity for integrated approach is further elaborated in Supplementary Discussion 1.

Natural systems and their associated processes are governed by intricate non-linear dynamics, potentially culminating in irreversible changes when tipping points are breached[34]. These critical thresholds can trigger a destabilizing regime shift, with profound repercussions on the monetary value of income derived from ES[35]. Biodiversity loss and climate change both hold the potential to push natural systems beyond tipping points from which recovery may prove unattainable[36]. While the scientific community is increasingly engaging with these challenges, numerous uncertainties persist.

Our study shows that the EA economy and banks are critically dependent on ES. The available data and current state of knowledge provide a foundational basis to support timely, nature-aligned decision-making, provided that urgent action is taken while the window of opportunity remains open. However, our analysis also highlights limitations, particularly regarding data availability, methodological constraints, and modeling capacities, which may hinder comprehensive risk assessments and policy formulation.

The ENCORE dataset used in our study neither account for the interconnections between different ES, nor between biodiversity and ES. This may result in an underestimation of the economic and financial risks associated with nature degradation[37,38]. To more accurately assess the economic importance of these services, it will be essential to consider these interconnections and the potential cascading effects that may arise from the ecosystem degradation and biodiversity loss[39]. Addressing these cascading effects within a more integrated framework will also require incorporating double materiality at the company level, enabling a comprehensive analysis of the interconnections between ecosystem degradation, biodiversity loss, and the associated physical and transition risks.

Ecosystem dependency scores here used are spatially independent. However, ecosystems and their state are highly location-specific, and so is the level of support they provide to economic activities. Ecosystems often facilitate the flow of services across regions[40]. This is particularly important, as the balance between ES supply and demand depends on local ecosystem conditions. Future research should therefore aim to disentangle and more precisely capture the localized dynamics of economic dependence on ecosystems[41] by incorporating more granular data on ES and spatially explicit ecological information.

In our analysis we do not adequately capture the effects that biodiversity loss can have on ecosystem functioning and the provision of ES. The loss of biodiversity can lead to a decline in the efficiency and stability of ecosystems, resulting in reduced capacity to provide essential services[42,43]. A comprehensive global analysis of the pressures funded by banks will be essential for a more thorough assessment of the cumulative impacts on global biodiversity[44,45].

It is important to mention that the ENCORE dataset is not a comprehensive ecological tool and should not be used as such. The ENCORE dataset serves as an important foundational effort to connect economic activities with ES. Recently, an updated ENCORE version was released (https://encorenature.org/en, July 2024), aligned with the SEEA EA ecosystem classification, introducing enhancements including refined ecosystem service categorization, materiality ratings, and an expanded classification of economic activities, among other improvements. Future analyses may use this update to produce more nuanced and detailed results. Nevertheless, the overall findings and conclusions of this study remain robust and valid.

Future research efforts should prioritize the development of integrated scenario narratives and advanced modeling frameworks to capture the interconnected and mutually reinforcing effects of climate change and biodiversity loss on both physical and transition risks (Supplementary Discussion 1). This requires a systemic approach that accounts for feedback loops, non-linear dynamics, and cross-sectoral dependencies, enabling a more accurate assessment of risks and their implications for financial stability and economic resilience.

Methods

Financial and economic datasets

The AnaCredit dataset contains detailed information on individual bank loans in the EA[46] harmonised across Member States. EA banks report information on loans towards companies with commitment of at least €25000. Our sample is based on December 2021 and counts for more than €4.3 trillion in corporate loans to around 4.2 million companies issued by around 2500 unique consolidated banks headquartered in EA. The loans covered by the dataset consist of conventional lending products extended to legal entities. Analysed loans represented 26% of the total bank loans portfolios in the euro area in December 2021 and around 75% of all the loans extended to euro area companies. It is important to mention that the majority of euro area bank loans in end-2021 was towards households (40%), however it is not yet possible to properly assess the dependencies on ecosystem services for this economic sector due to lack of granular information on households. The distribution of loans analyzed across sectors is as follows: real estate accounts for 26%, manufacturing 15%, wholesale and retail trade 12%, construction 6%, with the remaining 41% allocated to various other sectors.

Due to confidential nature of the AnaCredit dataset, the bank-level data cannot be displayed and shared. All our results are therefore aggregated on country and/or region and sector level. Additional regulatory financial confidential data is used to obtain various financial information of companies and banks, namely Orbis (a global company database), iBACH (profit and loss data of companies) and FINREP/CONREP (financial reporting frameworks).

Climate risk scores

The climate data from the first European economy wide stress test[10] is used here and consists of risk scores for five different climate hazards: droughts, heat waves, floods, sea level rise and wildfires. The drought risk score measures projected changes in drought patterns, integrating indicators that measure inter-annual variability, and absolute and relative percent changes in supply and demand for surface water. The sea level rise score estimates the absolute and relative increase in the frequency of coastal floods. The heat stress score measures the relative change in the frequency and severity of hot days and average temperature. The flood risk score measures the frequency of future rainfall events, and the intensity of prolonged periods of heavy rainfall. Lastly, the wildfire score is built based on soil moisture deficit[47].

All the risk scores represent intensity of exposure to climate hazards for all the companies in our study, based on their location and economic activity. Each climate hazard is converted into a standardized score ranging from 0 to 1: the higher the score, the more frequent and intense the hazard is, the stronger the impact on a given company and, consequently, the higher its losses[48]. Calculation of climate risk scores is based on the CMIP5 climate projections (18 climate models) for mid-century (2041-2050), following high-end emission scenario RCP8.5[47]. The RCP8.5 scenario was chosen to assess tail risks, as worst-case scenarios are essential for evaluating the resilience of the financial system under extreme but plausible conditions, aiding in financial stability assessment[49].

Ecosystem service demand and supply

ES arise from the interplay between the biophysical capacity of ecosystems to provide services independently of their use (ES potential) and the needs of economic sectors and society, irrespective of actual availability (ES demand). When ES potential and demand are aligned, the resulting actual flow of ecosystem services is generated and captured in the System of Environmental-Economic Accounting-Ecosystem Accounting (SEEA EA) supply-use tables[20]. Conversely, when demand exceeds potential, ecosystems are unable to fulfill the requirements of the economy and society, resulting in an ES mismatch that highlights ecosystem vulnerabilities and nature-related risks. In this study, we use ES mismatch metrics (https://ecosystem-accounts.jrc.ec.europa.eu/) to quantify the share of bank lending directed toward economic activities exhibiting different degrees of flood protection mismatch across the euro area.

Dependency of economic activities on ecosystem services and input/output table

The ENCORE dataset[14] provides assessment of industries' dependency on ES such as flood and storm protection, carbon uptake and storage and soil erosion control. Specifically, ENCORE provides dependency on 21 ES (Fig. 2b) and ranges from "no dependency" to "very high"; the range has been converted to a quantitative scale (from 0 to 1) and has been extensively used in the literature of financial risk assessment[9,50,51]. The dependency scores of ENCORE are location-independent. Additionally, the dependency scores are provided on a discrete scale and, while converting them to numerical scale, we implicitly assume a linear relationship between ecosystem degradation and economic damages.

To overcome assumption on spatial independence of sectoral dependence on ecosystems, we use supply chain information from input-output table EXIOBASE[52]. EXIOBASE is an environmentally extended multi-regional input-output (EE-MRIO) database that details the input requirements needed for each sector in a given country to produce its output. This data enables the assessment of: (i) the supply chain dynamics for each country-sector combination, and (ii) the significance of a specific economic sector within a country in producing a unit of a given good.

This study is based on the ENCORE dataset from 2021. In July 2024, after this study was finalised, an updated version became available (https://encorenature.org/en), introducing several improvements. These include alignment with the SEEA EA ecosystem classification, refined ecosystem service categorization, materiality ratings, and an expanded classification of economic activities.

Dependency of economic sectors on ecosystem services

For each borrower (all the companies analysed) we compute two types of dependencies: the direct dependency and the indirect one through supply chain linkages. It is important to clarify that these definitions are based solely on the company's role within the supply chain, rather than being derived from broader ecological perspectives. The direct dependency for each of the 21 ES is obtained from ENCORE (Supplementary Fig. 1) and is a continuous measures between 0 (no dependency) and 1 (high dependency).

The indirect dependency varies according to the sector and the country where company's headquarters are located. We compute the indirect dependency for a company in sector j headquartered in country c as a weighted average of the direct dependency scores $DS^{c',j'}_{direct}$ of all upstream suppliers (c', j'), with weights proportional to each supplier's share of total inputs into (c, j):

$$DS^{c,j}_{indirect} = \sum_{c' \in C} \sum_{j' \in S} w_{(c,j)\to(c',j')} \, DS^{c',j'}_{direct},$$

where the input share weights are computed from the Leontief inverse:

$$w_{(c,j)\to(c',j')} = \frac{L_{(c,j),(c',j')}}{\sum_{\tilde{c} \in C} \sum_{\tilde{j} \in S} L_{(c,j),(\tilde{c},\tilde{j})}}.$$

These weights are the share of total inputs drawn from the Leontief inverse L coming from each supplier node (c', j'). Because L (and thus the w) depends on the company's country c as well as its sector j, two companies in the same sector but headquartered in different countries will generally have different input share structures and hence distinct $DS_{indirect}$, even if their direct dependency DS_{direct} is identical.

The two dependencies are then aggregated in one single total dependency for each company as follows:

$$DS^{c,j}_{tot} = DS^{c,j}_{direct} + (1 - DS^{c,j}_{direct}) \times DS^{c,j}_{indirect}$$

where DS_{direct} and $DS_{infirect}$ represent the direct and indirect dependencies, respectively, and are continuous measures between 0 (no dependency) and 1 (high dependency). Although other types of aggregation are possible, we decided on this one to allow the indirect dependency to complement the direct one. The total dependency can be thus seen as a weighted average, which generates a 'leveling' effect (indirect dependency will be more important for a company with lower direct dependency).

The dependency scores for individual companies are then aggregated at the bank level. We use the AnaCredit financial dataset to evaluate the amount of loans granted to companies by different banks. By using banks' loans as weights, we compute each bank's dependency score as a weighted average of the ES dependencies of the companies to which the bank lends. This approach reflects the extent to which the loans provided by each bank are dependent on multiple ES.

Biodiversity footprint

While exposure assessment is aimed at gauging physical risk, analysis of the impact (or footprint) of companies and banks lending to them can be used to assess transition risk. It is highly possible that the economic activities with the highest footprint are also the ones likely to face nature-related transition risks as a result of additional restrictions/bans following the implementation of nature conservation policies.

The GLOBIO model[53,54] is at the basis of the biodiversity footprint assessment. GLOBIO is a global model of biodiversity intactness, measured in mean species abundance (MSA) as a function of different anthropogenic pressures. The MSA values are determined by dividing the abundance of each species found in relation to a given pressure by its abundance in an undisturbed situation[53,54]. Pressures included are climate change, land use (including fragmentation), roads, atmospheric nitrogen deposition and hunting.

To link to the multi-regional input-output model (MRIO), we use country specific biodiversity loss factors derived from GLOBIO, version 3.5[54]. Biodiversity loss factors express the area integrated MSA loss due to a given pressure (in MSA-loss.ha)[55]. In our specific case, we consider two main pressures: land use and climate change. Land use directly impacts biodiversity through eradication of natural habitat and indirectly through human encroachment and habitat fragmentation[55]. We use country specific coefficients to derive biodiversity loss factors due to land-based pressure. On the other hand, GHG emitted contribute to future global climate change and will cause disruption in species distributions and abundance.

The determinants of these pressures for the companies considered in our study are obtained from EXIOBASE which maps 417 emission categories and 662 material and resources categories. EXIOBASE provides data on 27 air pollutants and three land-use categories (cropland, grazing land,

and forest), allocated to 16 sectors of biomass extraction[52]. The emissions are obtained by combining activity data with consolidated sector emission factors, while land-use is obtained mainly from FAO and FAOSTAT.

Time- and area-integrated loss in MSA per unit of CO_2 emissions for a time horizon of 100 years (consistent with the IPCC) is used for our study: 4.37×10^{-5} MSA-loss.ha.yr/kg[45]. The time scale of integration is chosen to prioritize the impact of GHG with longer lifetime in the atmosphere (such as CO_2 and N_2O), considering the impacts that happen a century after the emissions occur[56].

On the other hand, for land use we consider cropland, grazing land and forest areas, which are converted to MSA losses using country specific loss factors[55]. They calculated these values by converting the habitat replacement caused by land use into gridded MSA losses and then aggregated to country specific loss factors for each pressure. It is important to notice that EXIOBASE does not provide data on urban areas and roads, which are therefore not considered as pressures in this study.

Both pressures are converted into MSA losses and aggregated at sector-level by country. Dividing the total MSA loss by the output, it is possible to obtain the MSA loss equivalent caused by production of €1 million (the direct intensity vector F). However, the latter does not consider the intermediate sales between sectors in the economy. To consider these intermediate flows it is necessary to compute the so-called inverse Leontief:

$$L = (I - A)^{-1}$$

where A is the matrix of technical coefficients. The elements of this matrix are computed as $a_{i,j} = z_{i,j}/x_j$ where z represents the intermediate relationship flows matrix obtained from EXIOBASE while x is the vector of total output for each of the combinations of sectors/countries considered. The matrix A contains the production inputs for the product of a given sector/region (column) and therefore indicates how much of various products are needed to produce 1 unit of output. This, however, refers only to the first step of imports, which in turns will need other intermediate ones:

$$F_{tot} = F \times L$$

Combining this information with the direct intensity vector allows to compute the total amount of MSA impact that occurs in the country where the output is produced. The Leontief could be seen as a geometric series representing all the intermediate steps of production. Moreover, given the importance of locating where emissions and land use take place during this chain, we expand the previous matrix product and keep the intermediate products without summing them. This provides a country-sector representation of the impacts along the supply chain:

$$F_{tot} = L' \times diag(F)$$

By subtracting from the diagonal F it is possible to obtain the upstream impact caused by the import of intermediate goods necessary to produce €1 million worth of goods in a given sector. This is important to allocate the total impacts caused by the flows of intermediate goods to the relevant sector and country.

Climate-nature nexus and network analysis

To demonstrate the potential amplification effect of compound shocks in climate and nature space, we first analyse the exposure of companies to: (i) drought and surface water provision, and (ii) flood risk and flood protection from vegetation. The amount of loans given to companies is then analysed for different risk levels of climate hazards and dependency on ES.

Network analysis is used to visualize the relationship between different climate and nature risk drivers in the EA economic space. The network is built combining the company-level information on their exposure to climate hazards and their dependency on ES. In particular, a weighted indirect network shows connections among physical climate risks and dependency on ES (nodes), where the weight of the edge connecting two different nodes is determined by the average value of the multiplication of: (i) companies' physical climate risk scores for two different climate hazards, (ii) physical risk score for climate hazards and dependency score for ES, or (iii) dependency scores for two different ecosystems services, depending on the nature of the nodes the edge is linking.

The network shows clusters of climate hazards and ES, and related connections that highlight the amplification effects of climate and nature risk drivers. These communities have been identified via Louvain community detection algorithm, which aims to maximize the global modularity of the network, defined as the difference between the density of links within communities compared to density of links between communities. Starting from singleton partitions, where each node is its own community, the algorithm moves each node to the community whose modularity would increase the most; once the local maximum of modularity is reached (i.e. no modularity increase is possible), all the nodes in the same community are grouped together in a new network[57].

To explore how these connections may evolve in the future, we construct a network based on climate risk scores for the mid-century time horizon (2041-2050). It is important to highlight that the dependency scores on ecosystems reflect the potential risks that could materialize in the event of ES degradation.

Data availability

The data used to support the analysis on dependency of the euro area economy and banks on ecosystem services are available as follows: (i) ENCORE materiality scores at https://encorenature.org/en/explore, and (ii) EXIOBASE supply use tables at https://www.exiobase.eu/. Financial and economic datasets used to calculate the dependency consist of: (i) AnaCredit (detailed information on individual bank loans), (ii) FINREP/CONREP (financial reporting frameworks), (iii) Orbis (a global company database) and (iv) iBACH (profit and loss data of companies). AnaCredit,FINREP/CONREP, and iBACH are confidential datasets (REGULATION (EU) 2016/867 OF THE EUROPEAN CENTRAL BANK, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016R0867) and cannot be shared. Orbis requires the purchase of a license. The data that support the findings of this study are available from Four Twenty Seven (currently Moody's ESG Solutions) but restrictions apply. Data from Four Twenty Seven are proprietary and covered by Non-Disclosure Agreement, and so are not publicly available. Access to the data may be granted with permission from Moody's ESG Solutions.

Code availability

The Python (version 3.9) and R (version 4.1.0) were used to prepare the code to perform the dependency analysis, biodiversity footprint and the network analysis. The code is available at: https://github.com/aceglar/ecosystems/. Restrictions apply to the availability of the data underlying the analysis.

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Author contributions

A.C. led the conceptualization. A.C., A.M. and A.T. prepared the first draft of the manuscript. S.B., C.L., A.M. and A.C. prepared the data, conducted the analysis and analysed the results. I.H. and L.P. contributed to writing according to their areas of expertise. A.C. led the paper revisions.

Competing interests

The authors declare no competing interests.

Additional information

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