Project acronym:	RAINFOREST
Title:	Co-produced transformative knowledge to accelerate change for biodiversity
Grant agreement number:	101081744

Deliverable 4.1

Quantifying climate and biodiversity footprints of companies and investment portfolios

Lead party for deliverable:	RU
Document type:	Deliverable
Due date of deliverable:	13-05-2025
Actual submission date:	30-05-2025
Version:	1.0
Dissemination level:	Public
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This project is funded by the European Union's Horizon Europe research and innovation programme under grant agreement no. 101081744.

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TABLE OF CONTENTS

RAINFOREST PARTNERS 3
TABLE OF CONTENTS 4
RAINFOREST PROJECT SUMMARY 5
QUANTIFYING CLIMATE AND BIODIVERSITY FOOTPRINTS OF COMPANIES AND INVESTMENT PORTFOLIOS 6
EXECUTIVE SUMMARY 7
1 BACKGROUND 8
2 DEVELOPING A FRAMEWORK FOR ASSESSING PORTFOLIO FOOTPRINT 10
3 SECTOR AVERAGE CLIMATE CHANGE AND BIODIVERSITY LOSS FOOTPRINT INTENSITIES 11
4 SCOPE 3 IMPACTS DOMINATE ACROSS THE VALUE CHAIN 13
5 A SMALL NUMBER OF COMPANIES DRIVE A LARGE SHARE OF IMPACTS 15
6 PORTFOLIO FOOTPRINTS 19
7 RECOMMENDATIONS 20
REFERENCES 23
AUTHOR LIST 25
SUPPLEMENTARY INFORMATION 26

RAINFOREST PROJECT SUMMARY

Co-produced transformative knowledge to accelerate change for biodiversity

Food and biomass production systems are among the most prominent drivers of biodiversity loss worldwide. Halting and reversing the loss of biodiversity therefore requires transformative change of food and biomass systems, addressing the nexus of agricultural production, processing and transport, retailing, consumer preferences and diets, as well as investment, climate action and ecosystem conservation and restoration. The RAINFOREST project will contribute to enabling, upscaling and accelerating transformative change to reduce biodiversity impacts of major food and biomass value chains. Together with stakeholders, we will co-develop and evaluate just and viable transformative change pathways and interventions. We will identify stakeholder preferences for a range of policy and technology-based solutions, as well as governance enablers, for more sustainable food and biomass value chains. We will then evaluate these pathways and solutions using a novel combination of integrated assessment modelling, input-output modelling and life cycle assessment, based on case studies in various stages of the nexus, at different spatial scales and organizational levels. This coproduction approach enables the identification and evaluation of just and viable transformative change leverage points, levers and their impacts for conserving biodiversity (SDGs 12, 14-15) that minimize trade-offs with targets related to climate (SDG13) and socioeconomic developments (SDGs 1-3). We will elucidate leverage points, impacts, and obstacles for transformative change and provide concrete and actionable recommendations for transformative change for consumers, producers, investors, and policymakers.

Policy-Business Brief

QUANTIFYING CLIMATE AND BIODIVERSITY FOOTPRINTS OF COMPANIES AND INVESTMENT PORTFOLIOS

EXECUTIVE SUMMARY

As climate change and biodiversity loss accelerate, understanding corporate environmental impacts has become a priority for governments, companies, and investors. This study evaluates the greenhouse gas (GHG) and biodiversity footprints of 2563 companies in the MSCI ACWI, providing a comprehensive analysis across sectors, the identification of companies with highest footprints, and the quantification of investment portfolio-level footprints.

Our findings reveal that GHG footprints (in tonnes of CO_2-eq, excluding emissions from land use and land cover change) concentrate in oil and gas mining and chemicals sectors, while biodiversity footprints (in MSA-loss·km^2) include agriculture and food sectors in addition to the oil, gas, and chemicals sectors. The majority of the footprints arise from indirect (scope 3) activities across the value chain, such as upstream emissions from raw material extraction, or downstream emissions from final demand. The financial intermediation sector also contributes to the GHG and biodiversity footprints. These impacts stem predominantly from downstream impacts, primarily through capital allocation, that is, the GHG and biodiversity footprints caused by the activities of companies that receive investment or financing. Notably, a relatively small number of high-impact companies account for a significant portion of the estimated GHG and biodiversity footprints within the MSCI ACWI, highlighting opportunities for targeted engagement and regulatory intervention.

By advancing portfolio footprint metrics and emphasizing value chain interlinkages, this study provides a foundation for more transparent environmental disclosure and informed investment decision-making.

1 BACKGROUND

Climate change and biodiversity loss are mutually reinforcing threats that pose far-reaching risks to ecosystems, economic activities and society[1,2]. Climate change causes biodiversity loss via shifts in environmental conditions. Biodiversity loss, in turn, undermines nature's capacity to sequester carbon, further aggravating global warming[3]. This feedback loop generates various risks for economic activities such as reduced yields due to droughts or insufficient pollination[2].

Companies have great potential to mitigate climate change and biodiversity loss[4-6]. A significant proportion of global greenhouse gas (GHG) emissions can be directly attributed to business activities such as resources extraction and industrial production[7]. For example, 100 active fossil fuel companies have been responsible for about 70% of the global industrial GHG emissions since 1988s[8]. However, company-level environmental footprint disclosure remains inadequate relative to the urgency of climate and biodiversity action[9]. According to the GHG Protocol, one of the world's leading GHG reporting standards, companies are required to report scope 1 (i.e., direct emissions from owned or controlled operations) and scope 2 emissions (i.e., indirect emissions from purchased energy). Scope 3 emissions (i.e., all other indirect emissions that occur up and down the value chain) are voluntarily disclosed, even though they typically represent the largest share of total company footprints[10]. Disclosure of biodiversity footprints is even more limited and lacks standardization[11].

As climate and biodiversity regulations become increasingly strict, investors can allocate a greater share of capital to companies with lower GHG and biodiversity footprints, in an effort to reduce climate- and biodiversity-related risks associated with their investments and to align investments with sustainability goals[12,13]. Prerequisite for this is a reliable and comparable information on companies' GHG and biodiversity footprints[14]. Responding to these evolving demands, the European Union introduced the Corporate Sustainability Reporting Directive (CSRD) in 2023. CSRD mandates large companies to report the environmental risks they are exposed to and the environmental impacts that their activities cause from 2026 onwards[15]. CSRD can provide critical information to investors and financial institutions who rely on environmental performance metrics to evaluate risk and guide capital allocation.

While the CSRD represents a major step forward in mandating company sustainability disclosure, it raises the challenge of how such disclosure can be implemented consistently and comparably across companies, especially for scope 3[16]. Despite technical guidance provided by the GHG Protocol, scope 3 emissions disclosures remain incomplete and inconsistent[17]. For instance, only 40% of companies reporting to the Carbon Disclosure Project (CDP) disclose scope 3 emissions[9], and they report them in different ways, making it difficult to compare emissions across companies. Moreover, the carbon footprints of different companies are non-additive due to their overlapping value chains [18]. To deal with the problem of double counting, recent studies have showed that top-down based environmentally extended multiregional input-output (EEMRIO) approach becomes a good fit in the context of company level assessment[18-22]. This method ensures comprehensive coverage of all indirect environmental impacts associated with an economic sector, reflecting its completeness in covering economic transactions globally[23].

Compared to traditional demand-driven IO model, we developed a unified EEMRIO framework with hypothetical extraction approach to assess the climate and biodiversity footprints related to individual companies as well as to investment portfolios. To quantify the footprints of investment portfolios, we regard the companies in a portfolio as a whole and extract the gross output associated with the portfolio[18,19]. The resulting gross climate and biodiversity impacts of the investment portfolio are then quantified as the difference between the original economic system measured by IO and the system from which the investment portfolio-related economic activities have been extracted. This approach enables the estimation of the environmental footprints attributable to investment portfolio, offering insight into the potential risks that climate change and biodiversity loss pose to company's economic activity, while also helping investors assess the climate and biodiversity impacts of their capital allocation.

Here we look at companies from the MSCI All Country World Index (ACWI) 2022, including 2563 large- and mid-sized companies from 23 developed markets and 24 emerging markets[24]. The index covers about 85% of the global investable equity opportunity set, providing a representative of global market capitalization and a robust basis for understanding the company and portfolio-level GHG and biodiversity footprints.

2 DEVELOPING A FRAMEWORK FOR ASSESSING PORTFOLIO FOOTPRINT

In response to increasing regulatory demand for environmental transparency, we develop a framework to assess the GHG and biodiversity footprints of investment portfolios. The method builds on EEMRIO assessment and uses environmental extensions from EXIOBASE[25], using data for the year 2022 (see text section S1). We consider climate change and biodiversity loss footprint indicators. We use country-level GHG emissions and land use data from EXIOBASE environmental extensions[25] to quantify climate change and biodiversity footprint (see text section S2).

To estimate company-level footprints downscale the EEMRIO the sector per country data to company-level data based on company financial revenues relative to the total revenue of the country-sector. We use the S&P Capital IQ database[26], for company-level revenue data, which provides disaggregated revenue information across detailed geographic and sectoral segments (see text section S3). Investment portfolio footprints are calculated as footprint intensities (i.e., tonne CO_2-eq or MSA-loss·km^2 per million euro invested), based on the footprint intensity of each company and the corresponding investment weight in the portfolio (see text section S4). The resulting portfolio-level footprint intensity can then be scaled by the actual amount invested in the MSCI AWCI to obtain the total absolute footprint associated with the portfolio. All data used in this analysis refer to the fiscal year 2022.

3 SECTOR AVERAGE CLIMATE CHANGE AND BIODIVERSITY LOSS FOOTPRINT INTENSITIES

To explore sector-level patterns in climate change and biodiversity loss, we analyse the footprint intensities of companies classified by their sectors within the MSCI ACWI. Fig. 1 shows that climate change and biodiversity loss footprint intensities vary considerably across economic sectors. In terms of climate change impacts, sectors such as coal mining (COL), distribution and trade of electricity (DTE), non-metallic mineral products (NMM), gas manufacture and distribution (GAS), and metal production (MET) exhibit significantly higher climate footprint intensities. These sectors are either directly involved in energy production and distribution or represent energy-intensive heavy industries. In contrast, sectors with the highest biodiversity footprint intensity, such as the agricultural (AGR), food production meat (FDM), seafood (SEA), dairy products (DAI), and paper products (PAP) sectors, are predominantly linked to land use. Coal mining (COL) and distribution and trade of electricity (DTE) also show high biodiversity intensities, indicating a nexus between climate change and biodiversity loss.

These difference in climate change and biodiversity loss footprint intensities may affect investment decisions of financial institutions. Businesses operating in sectors with high climate and biodiversity footprints might face financial risks as climate and biodiversity regulations become increasingly strict. Ranking and prioritizing sectors according to the materiality of their climate change and biodiversity loss footprint intensities can help guide the implementation of portfolio footprint assessments as long as company-level data remains limited.

Fig. 1 | Sectoral intensity of GHG and biodiversity footprints averaged across MSCI ACWI companies within each sector. **a**, GHG footprint intensity (tonnes CO_2-eq per million euro) by sector. **b**, Biodiversity footprint intensity (MSA-loss·km^2 per million euro) by sector. See Table S1 for sector abbreviations.

4 SCOPE 3 IMPACTS DOMINATE ACROSS THE VALUE CHAIN

While all businesses exert impacts on climate and biodiversity, a large portion of these impacts occur indirectly through their value chains and are often underreported. Our analysis shows that more than 60% of both climate change and biodiversity loss footprints are attributed to indirect impacts (scope 3) along the value chain, encompassing both upstream and downstream activities (Fig.2a). This highlights the importance of considering the entire value chain rather than focusing solely on direct operations (scope 1) or energy use (scope 2).

Oil and gas mining (OGM), chemical products (CHE), and financial intermediation (FIN), rank at the top for both climate change and biodiversity loss footprints (Fig. 2b and 2c). Together, these three sectors contribute about 30% of the total climate change and biodiversity loss footprints. Moreover, the top 15 sectors cumulatively account for 71-75% of the overall footprints.

The footprint structures differ substantially across sectors. Oil and gas mining and chemical products exhibit high levels of direct climate change footprints, primarily due to extraction and refining of fossil fuels. They also cause direct biodiversity loss due to land use for mining activities. In contrast, the financial intermediation and wholesale and retail trade sectors have low direct environmental footprints compared to the oil and gas mining sector. However, financial institutions can have significant indirect footprints through their investments, and retail companies can have significant upstream footprints through the production of their products and downstream footprints during consumer use of the products.

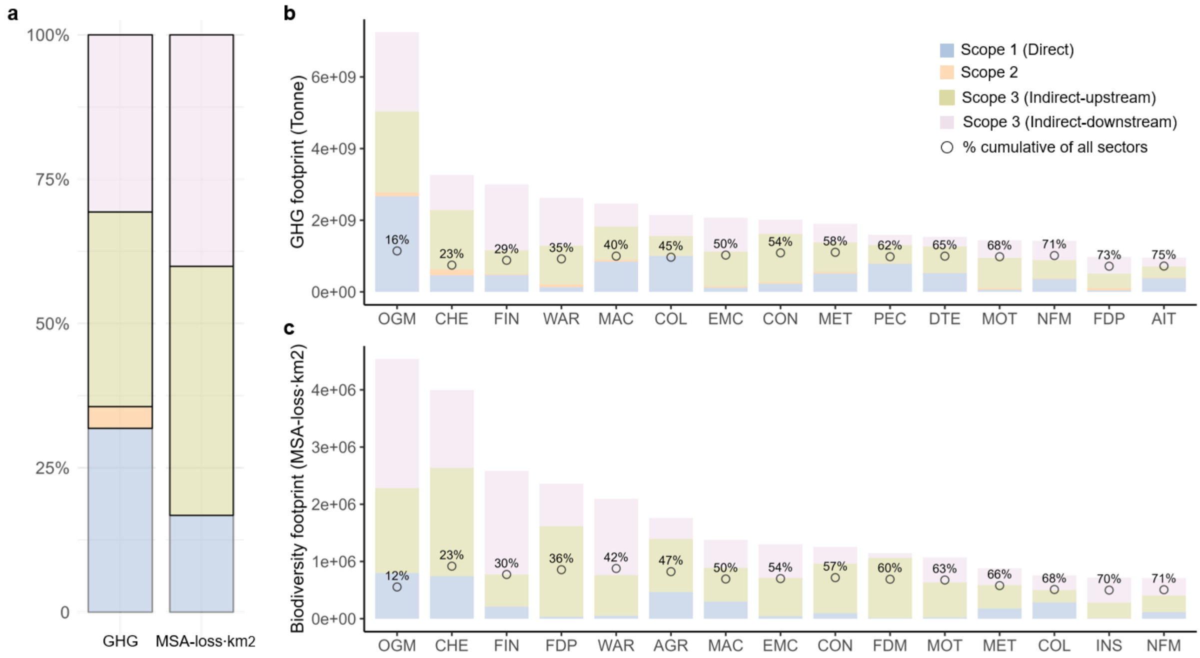

Fig. 2 | GHG and biodiversity footprints of MSCI ACWI companies by sector. **a**, Share of total GHG and biodiversity footprints by scope. **b**, Top 15 sectors with the highest climate change footprint. **c**, Top 15 sectors with the highest biodiversity footprint. The circle indicates the cumulative percentage contribution across all sectors. OGM: Oil and gas mining; CHE: Chemical products; FIN: Financial intermediation; WAR: Wholesale and retail trade; MAC: Manufacture of machinery and equipment; COL: Coal mining; EMC: Manufacture of electrical machinery and apparatus; CON: Construction; MET: Metal production; PEC: Production of electricity by coal; DTE: Distribution and trade of electricity; MOT: Manufacture of motor vehicles, trailers and semi-trailers; NFM: Mining of non-ferrous metal ores and concentrates; FDP: Food production plant; AIT: Air transport; AGR: Agriculture; FDM: Food production meat; INS: Insurance and pension funding.

5 A SMALL NUMBER OF COMPANIES DRIVE A LARGE SHARE OF IMPACTS

As shown in Fig. 3, both GHG and biodiversity footprints are highly concentrated among a relatively small number of companies within the MSCI ACWI. The top 100 highest-impacting companies account for 55% of total climate change footprints and 59% of biodiversity loss footprints, while the top 200 contribute more than two-thirds of the total climate change and biodiversity loss footprints.

The MSCI ACWI portfolio contains 72 companies in the oil and gas mining sector that together represent 26% and 33% of the companies in with the top 100 highest climate change and biodiversity loss footprints, respectively. Additionally, food-related sectors (including meat, seafood, plants, dairy, and beverages) constitute 15% of the companies with the top 100 highest biodiversity loss footprint.

When examining the footprint scopes, the top 100 companies are responsible for more than half of total footprints across direct (scope 1) and indirect (scope 2 & 3) categories for both GHG (Fig. 3b) and biodiversity footprints (Fig. 3d). This reinforces the findings that targeted engagement and action focusing on a small group of high-impact companies could yield substantial environmental benefits, particularly in sectors that dominate the value chains.

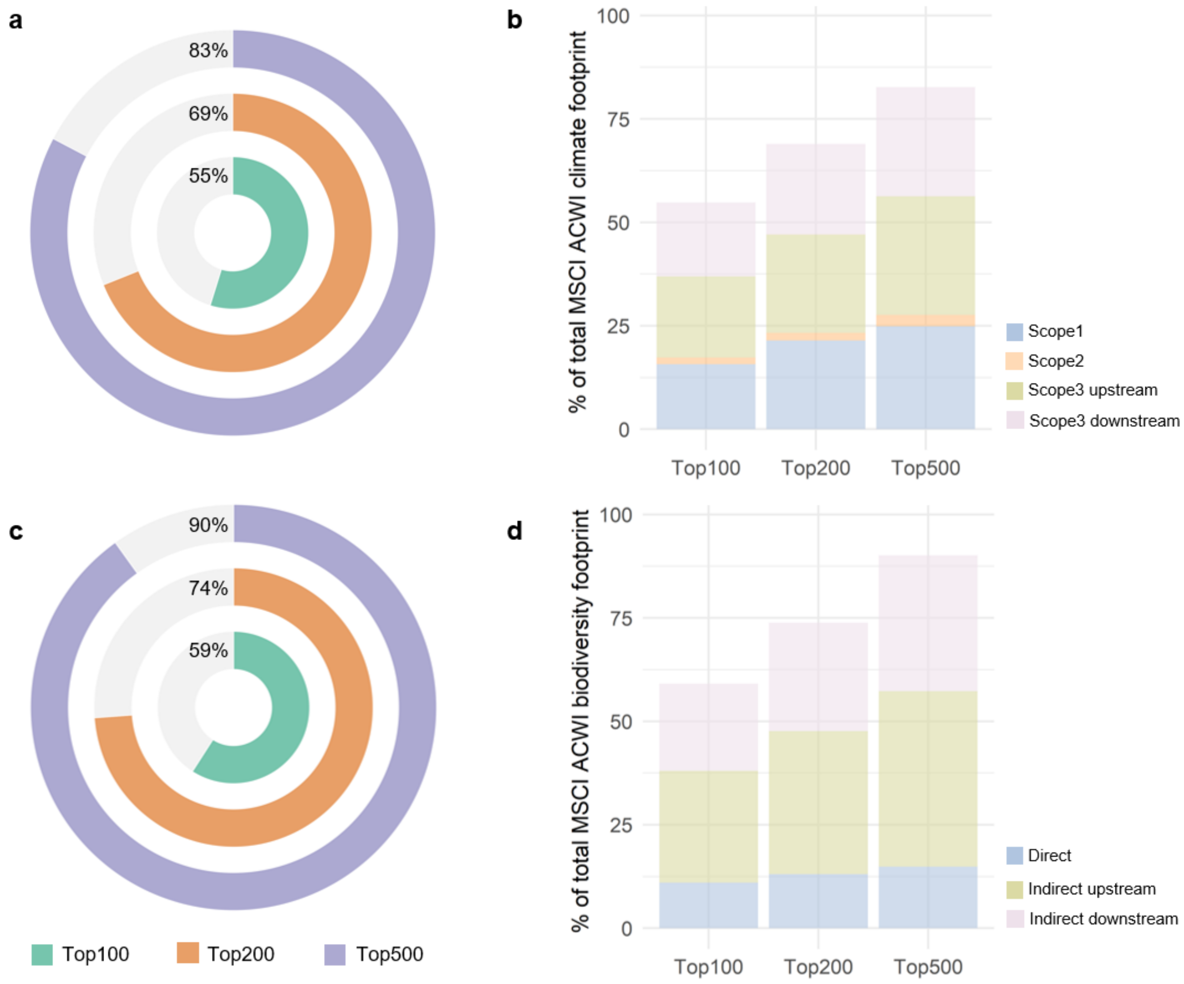

Fig. 3 | Share of climate change and biodiversity loss footprints by top emitting companies in MSCI ACWI. a,b, GHG footprint (**a**) and scope share (**b**) of the top 100, 200, and 500 companies compared to total MSCI ACWI climate footprint. **c**,d, Biodiversity footprint (**c**) and scope share (**d**) of the top 100, 200, and 500 companies compared to total MSCI ACWI biodiversity footprint.

There is considerable variation in climate change footprint intensity (company footprint / company EVIC) between companies even within the same sector. For instance, OGM company 7 exhibits a climate change footprint intensity that is about 14 times higher than that of OGM company 1, despite both being classified as oil and gas companies. This illustrates that companies within the same sector can have substantially different environmental footprints due to differences in operational practices, production technologies, and sourcing value chains. These differences are crucial to consider when prioritizing companies for targeted engagement or regulation. In addition, some companies have typically high direct footprints (e.g., companies in the coal mining sector), while others have typically high indirect upstream or downstream footprints (e.g., companies in the construction or retail sectors, respectively). These distinctions highlight the need to adopt sector-specific strategies when addressing climate change footprints.

There is also notable variation in biodiversity loss footprint intensities across companies. For example, a supermarket chain has a biodiversity intensity roughly 7 times higher than that of a major food company. What they have in common, however, is the dominance of scope 3 upstream impacts, driven largely by the procurement of high-impact products such as crops and livestock. This reflects the significant role of the agricultural commodity supply chain in driving biodiversity loss, particularly through land use.

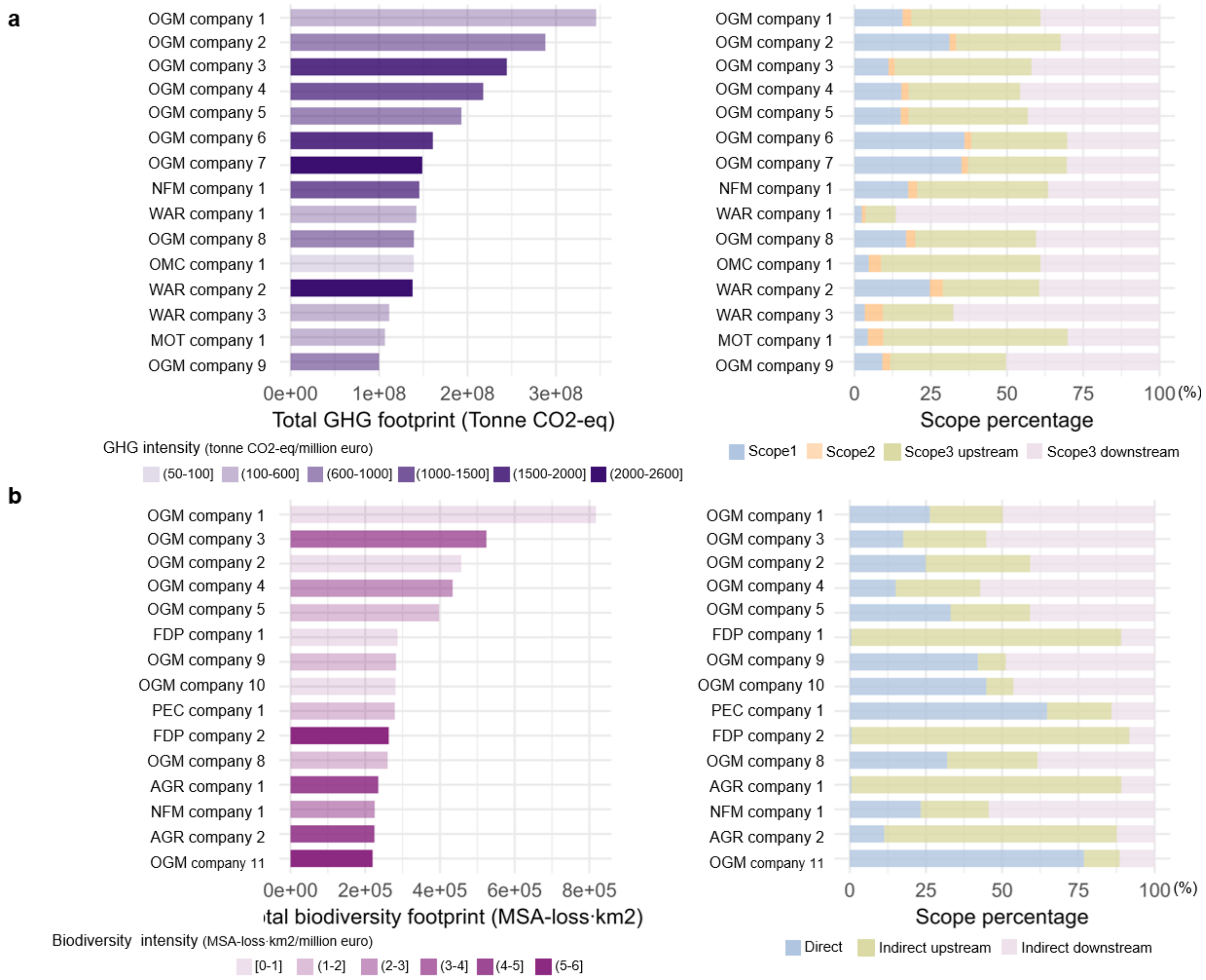

Fig. 4 | GHG and biodiversity footprints of top 15 highest-impact companies in the MSCI ACWI. a, GHG footprint. **b**, Biodiversity footprint. in each panel, the left-side bar represents each company's total footprint, filled by GHG or biodiversity intensity. The right-side bar shows the percentage share of direct (scope 1) and indirect (scope 2 and scope 3) impacts.

These insights emphasize that to adequately address climate change and biodiversity loss footprints, it is needed to go beyond aggregate footprints. Investors and regulators should also assess footprint intensity and the structure of emissions across value chains to better identify companies that are not only large emitters but also operationally inefficient or on high-impact activities through their value chain. By targeting companies with both high total footprints and high footprint intensities, and understanding the source of the footprints, financial institutions and policy makers can optimize the allocation of financial resources and policy strategies, enabling a more effective pathway to reduce environmental impacts related to economic activities.

6 PORTFOLIO FOOTPRINTS

Finally, we estimate the GHG and biodiversity footprint of the MSCI ACWI at the portfolio level, offering a methodology for investors to assess the climate change and biodiversity loss footprints of their investment portfolios. The MSCI ACWI represents a diversified investment pool of 2563 global publicly listed companies. It tends to be skewed towards companies from finance and technology sectors due to their large share in capital markets. While companies in these sectors typically have lower direct climate change and biodiversity loss footprints, they often play a key role in driving downstream impacts through their financing activities.

The overall climate change and biodiversity loss footprint intensities of the MSCI ACWI portfolio are, respectively 302.9 tonne CO_2-eq per million euro and 0.461 MSA-loss·km^2 per million euro. Assessing portfolio-level footprints enables investors to better understand and manage the climate and biodiversity-related risk embodied in their asset or loan portfolios. This also provides a foundation for aligning investment strategies with environmental targets and emerging disclosure frameworks.

7 RECOMMENDATIONS

Under the CSRD, companies are required to disclose environmental impacts of their activities, with climate change and biodiversity loss as two of the most important domains. Given the complex interlinkages across sectors, a company's environmental footprint extends well beyond its direct operations to its entire value chain[18,20]. These inter-sectoral connections can amplify risk propagation across the economy, potentially generating financial risks far greater than commonly estimated[27-29].

A key step to address climate change and biodiversity loss impacts is to assess and disclose full value chain company environmental impacts[14]. This assessment provides a critical baseline for companies, regulators, and investors to understand the climate change and biodiversity loss footprints of companies and their supply chains.

Once these impacts are identified and transparently disclosed, companies are better positioned to implement effective mitigation strategies, such as improving operational efficiency or considering environmental performance up- and downstream their value chain. Disclosure also enables investors to evaluate environmental performance more accurately, distinguishing between companies with high total environmental footprints and high environmental footprint intensities.

Our findings emphasize the importance of scope 3 impacts, which dominate in most sectors yet remain underreported in many environmental assessments[17]. Whether stemming from upstream resource extraction or downstream activities, these indirect impacts highlight the need for companies to adopt value chain wide and sector-specific strategies to reduce environmental impacts. Likewise, policymakers and investors should consider environmental footprints across the entire supply chain rather than focusing solely on direct impacts.

Importantly, a small number of high-impact companies account for a disproportionate share of total environmental footprints. Prioritizing these companies for engagement and targeted regulatory interventions could be an effective way to achieve transformative change for climate and biodiversity. Moreover, understanding the environmental footprint of investment portfolios, such as the MSCI ACWI, can help asset managers and financial institutions align capital flows with climate and biodiversity targets. While value chain governance and investment-based approaches offer important insights for reducing environmental footprints, it is critical to recognize that such solutions are challenging to implement. Source-level regulation, such as national environmental legislation to introduce carbon taxes or to curb land use change, often provides more direct and efficient means of mitigating climate change and biodiversity loss. Therefore, footprint assessments should be seen as complementary tools that inform and support both upstream regulatory efforts and downstream financial strategies.

Additionally, integrating biodiversity considerations alongside climate mitigation strategies in regulatory frameworks and investment decisions is essential not only for preserving ecosystems but also for ensuring long-term economic resilience[34,35]. Our analysis indicates that sectors with high climate change footprints also tend to exhibit high biodiversity loss. This illustrates the significant impact of climate change on biodiversity, therefore, sectors that contribute heavily to climate change also play a major role in driving biodiversity loss. Targeting these sectors may therefore yield co-benefits for both climate and biodiversity outcomes. Since climate change and biodiversity loss are inherently linked, tackling both in a coherent way is vital for achieving global sustainability goals.

Climate and biodiversity footprints provide a useful tool for portfolio hotspot analysis – to understand which companies should be prioritised for engagement or capital allocation decisions. However, due to their reliance on sectoral economic-environmental modelling approaches, our framework has certain limitations. Since the top-down EEMRIO approach is based on sector-country level averages and therefore cannot capture variations in footprint intensities between companies within the same sector-country combination. This implies that the approach may overlook the unique profile of a company. Additionally, mapping company revenue data from the S&P database into EXIOBASE classification leads to some loss of sectoral detail. While we preserve important distinctions in footprint sensitives sectors such as food production (e.g., animal-based, plant-based, fish, dairy, beverages), other sectors like chemicals are aggregated more broadly. For example, EXIOBASE does not differentiate between agricultural chemicals (e.g., fertilizer), industrial chemicals and pharmaceuticals, despite their different environmental impacts.

Nevertheless, the top-down EEMRIO offers valuable insights into the footprints related to investment portfolios. It allows for the identification of high-impact sectors and value chain stages that are most relevant for environmentally informed investment and policy strategies. Looking forward, decisions concerning individual portfolio companies should not rely on footprints alone. Engagement and capital allocation decisions require bottom-up assessment of company-specific value chains. A promising direction for future work is the development of hybrid approaches that integrate the granularity of bottom-up data with the systemic perspective of top-down models. Furthermore, expanding the analysis to multiple portfolio indices and incorporating time series data would enable tracking of trends and the evaluation of progress over time.

REFERENCES

1. Newbold, T., Oppenheimer, P., Etard, A. & Williams, J. J. Tropical and Mediterranean biodiversity is disproportionately sensitive to land-use and climate change. *Nat Ecol Evol* 4, 1630–1638 (2020).
2. Pörtner, H. O. et al. Overcoming the coupled climate and biodiversity crises and their societal impacts. *Science* vol. 380 Preprint at https://doi.org/10.1126/science.abl4881 (2023).
3. Keck, F. et al. The global human impact on biodiversity. *Nature* (2025) doi:10.1038/s41586-025-08752-2.
4. Cenci, S., Burato, M., Rei, M. & Zollo, M. The alignment of companies' sustainability behavior and emissions with global climate targets. *Nat Commun* 14, (2023).
5. Kılkış, Ş. et al. City-company collaboration towards aligned science-based target setting. *Nat Sustain* (2024) doi:10.1038/s41893-024-01473-w.
6. Etzion, D. Corporate engagement with the natural environment. *Nature Ecology and Evolution* vol. 4 493 Preprint at https://doi.org/10.1038/s41559-020-1142-5 (2020).
7. Bai, X. et al. Translating Earth system boundaries for cities and businesses. *Nature Sustainability* vol. 7 108–119 Preprint at https://doi.org/10.1038/s41893-023-01255-w (2024).
8. Carbon Disclosure Project. New report shows just 100 companies are source of over 70% of emissions. (2017).
9. Carbon Disclosure Project. Only 37% of Scope 3 emissions from European businesses are addressed by corporate decarbonization measures. (2023).
10. GHG Protocol. A Corporate Accounting and Reporting Standard. (2002).
11. Kareiva, P. M., Mcnally, B. W., Mccormick, S., Miller, T. & Ruckelshaus, M. Improving global environmental management with standard corporate reporting. *Proc. Natl Acad. Sci. USA* 112, 7375–7382 (2015).
12. Popescu, I. S., Hitaj, C. & Benetto, E. Measuring the sustainability of investment funds: A critical review of methods and frameworks in sustainable finance. *Journal of Cleaner Production* vol. 314 Preprint at https://doi.org/10.1016/j.jclepro.2021.128016 (2021).
13. Dietz, S., Bowen, A., Dixon, C. & Gradwell, P. Climate value at risk' of global financial assets. *Nat Clim Chang* 6, 676–679 (2016).
14. Wassénius, E., Crona, B. & Quahe, S. Essential environmental impact variables: A means for transparent corporate sustainability reporting aligned with planetary boundaries. *One Earth* vol. 7 211–225 Preprint at https://doi.org/10.1016/j.oneear.2024.01.014 (2024).
15. European Commission. DIRECTIVE (EU) 2022/2464 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting (CSRD). (2022).
16. Hertwich, E. G. & Wood, R. The growing importance of scope 3 greenhouse gas emissions from industry. *Environmental Research Letters* 13, (2018).
17. Klaaßen, L. & Stoll, C. Harmonizing corporate carbon footprints. *Nat Commun* 12, (2021).
18. Zhang, Z., Li, J., Wang, X., Chen, X. & Zheng, C. Leading global asset managers are crucial but off track in climate change mitigation. *One Earth* 101267 (2025) doi:10.1016/j.oneear.2025.101267.
19. Zhang, Z., Li, J. & Guan, D. Value chain carbon footprints of Chinese listed companies. *Nat Commun* 14, (2023).
20. Popescu, I. S., Schaubroeck, T., Gibon, T., Petucco, C. & Benetto, E. Investment funds are responsible for substantial environmental and social impacts. *Commun Earth Environ* 5, (2024).
21. Kulionis, V., Pfister, S. & Fernandez, J. Biodiversity impact assessment for finance. *J Ind Ecol* (2024) doi:10.1111/jiec.13515.
22. Popescu, I. S., Gibon, T., Hitaj, C., Rubin, M. & Benetto, E. Are SRI funds financing carbon

emissions? An input-output life cycle assessment of investment funds. *Ecological Economics* 212, (2023).
23. R.E. Miller & P.D. Blair. Input-Output Analysis: Foundations and Extensions. (Cambridge University Press, 2009).
24. MSCI. MSCI ACWI Index. (2023).
25. Stadler, K. et al. EXIOBASE 3: Developing a Time Series of Detailed Environmentally Extended Multi-Regional Input-Output Tables. *J Ind Ecol* 22, 502–515 (2018).
26. IPCC. Sixth Assessment Report (AR6) . (2021).
27. Schipper, A. M. et al. Projecting terrestrial biodiversity intactness with GLOBIO 4. *Glob Chang Biol* 26, 760–771 (2020).
28. Wilting, H. C., Schipper, A. M., Bakkenes, M., Meijer, J. R. & Huijbregts, M. A. J. Quantifying Biodiversity Losses Due to Human Consumption: A Global-Scale Footprint Analysis. *Environ Sci Technol* 51, 3298–3306 (2017).
29. Joos, F. et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis. *Atmos Chem Phys* 13, 2793–2825 (2013).
30. S&P Global. S&P Capital IQ. (2023).
31. Mandel, A., Battiston, S. & Monasterolo, I. Mapping global financial risks under climate change. *Nat Clim Chang* (2025) doi:10.1038/s41558-025-02244-x.
32. Battiston, S., Mandel, A., Monasterolo, I., Schütze, F. & Visentin, G. A climate stress-test of the financial system. *Nat Clim Chang* 7, 283–288 (2017).
33. Inoue, H. & Todo, Y. Firm-level propagation of shocks through supply-chain networks. *Nat Sustain* 2, 841–847 (2019).
34. Ortiz, A., Outhwaite, C., Dalin, C., & Newbold, T. A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. *One Earth* vol. 4, 1, 88-101 (2021).
35. Wintle, B., Bekessy, S., Keith, D., et al. Ecological-economic optimization of biodiversity conservation under climate change. *Nat Clim Chang* 1, 355–259 (2011).

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SUPPLEMENTARY INFORMATION

Text Section S1. Footprint calculation

Our assessment builds upon the Leontief demand-driven IO model, where the total output x of an economic sector in a country is derived as[23]:

$$x = (I - A)^{-1}y = Ly \qquad (1)$$

I is the identity matrix. A is the technology matrix representing the amount of intermediate inputs used in the production of one unit of output. L is the Leontief inverse matrix representing total requirements, and y is the final demand. Each element of the vector x represents a sector's total output, which cumulatively reflects contributions from different sources of value added throughout the production process.

Let V be a diagonal matrix of value added coefficients, where each diagonal element represents the share of value added in that sector's own total output. The value added can be expressed as:

$$v = Vx = VLy = V(I + A + A^2 + \cdots)y \qquad (2)$$

where $VA^n y$ is the value added induced by final output through a supply chain with n+1 production stages. In this view, value added accumulates across each production stage, reflecting the inter-sectoral dependencies within the economy. Moreover, since V is a diagonal matrix of value added coefficients, the multiplication of V and L results in a vector (VL) of which the sum of equals 1. Thus, VL can be interpreted as an allocation matrix that distributes total output across sectors based on their contribution to value creation[19].

Building on this, the cumulative output enabled by a sector's value added, denoted as $\tilde{x}$, can be expressed as:

$$\tilde{x} = VLLy = V(I + 2A + 3A^2 + 4A^3 + \cdots)y \qquad (3)$$

To calculate environmental footprint, we define F as a diagonal matrix of direct environmental intensity (e.g., GHG emissions per euro, or biodiversity loss per euro). The gross environmental footprints (e) generated during the cumulative output production process are then:

$$e = VLFLy = V(F + FA + AF + FA^2 + AFA + A^2F + \cdots)y \qquad (4)$$

Since *VL* reflects a supply-driven allocation and *FLy* captures demand-driven environmental pressures, this formulation integrates both upstream and downstream impacts across sectoral outputs[18].

Text Section S2. Climate and biodiversity indicators

For climate change, the GHG emissions contain a subset of gases responsible for global warming including carbon dioxide (CO_2), methane (CH_4), dinitrogen oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), which are aggregated into CO_2 equivalents (CO_2-eq) using their Global Warming Potentials (GWPs) over 100 years following the most recent IPCC assessment report[30].

To capture biodiversity loss, we use the loss in mean species abundance (MSA-loss) obtained from the GLOBIO4 model[31]. The MSA-loss indicator describes the local compositional intactness of a species community relative to an undisturbed natural reference situation, expressed as value between 0 (the species community is identical to the natural reference condition) and 1 (all species in the natural reference condition have disappeared). By considering the area over which biodiversity is affected, the biodiversity footprint indicator is expressed in MSA-loss·km^2.

We consider two main pressures affecting MSA from two main pressures, land use and climate change, and evaluated each pressure independently. For land use impacts on MSA-loss, we link the GLOBIO4 land use pressure-response relationships [31] to the EXBIOBASE land use classes including cropland, pasture, forestry, and urban area. For climate change impacts on MSA-loss, we calculate the global mean temperature increase based on the CO_2-equivalent GWPs per kg of GHG (CO_2, CH_4, and N_2O)[32] and link this to the climate change pressure response relationship of GLOBIO4[31]. Specifically, we distinguish CH_4 by fossil fuels and biogenic sources because the different GWPs[33]. For the GLOBIO4 climate change pressure-response relationship we derived the MSA-loss per degree of global mean temperature based on a temperature increase of 1.5°C. This is then multiplied by the total terrestrial surface area (excluding Greenland and Antarctica) to obtain the area-integrated MSA-loss per degree of warming.

Text Section S3. Company-level and sectoral-level footprint

We construct a bridge matrix that reflects the share of a company's revenue derived from different country-sector combinations To trace the value chain footprints associated with a specific sector *i* in region *r*, we apply a hypothetical extraction method. That is, we quantify the footprint of sector *i* in region *r* as the difference between the environmental footprint of the complete original economic system measured by the EEMRIO table and that of a hypothetical economy in which the activities of sector *i* in region *r* are removed:

$$e_{ri} = VLFLy - V^*_{ri}L^*_{ri}F^*_{ri}L^*_{ri}y^*_{ri} \qquad (5)$$

where $V^*_{ri} = V - V_{ri}$ is the value added matrix without sector *i* in region *r*. $L^*_{ri} = (I - A^*_{ri})^{-1}$, and A^*_{ri} is the intermediate input matrix excluding elements that related to sector *i* in region *r*. $F^*_{ri} = F - F_{ri}$, and F_{ri} is a diagonal matrix of the environmental intensity of sector *i* in region *r*. $y^*_{ri} = y - y_{ri}$, excluding the final demand that related to sector *i* in region *r*. The footprints can be further disaggregated into:

$$e_{ri} = \underbrace{VLF_{ri}Ly}_{direct\ (scope1)} + \underbrace{\underbrace{VLF^*_{ri}(Ly - L^*_{ri}y^*_{ri})}_{upstream} + \underbrace{(VL - V^*_{ri}L^*_{ri})F^*_{ri}Ly}_{downstream} - \underbrace{(VL - V^*_{ri}L^*_{ri})F^*_{ri}(Ly - L^*_{ri}y^*_{ri})}_{duplication}}_{indirect\ (scope2+scope3)} \qquad (6)$$

Scope 1 footprints capture the direct impact of sector *i* in region *r*. Scope 2 footprints reflect the upstream impacts related to the energy supply to sector *i* in region *r*. Scope 3 footprints reflect all other upstream as well as downstream impacts along the value chain of sector *i* in region *r*. Because downstream activities may re-import intermediate products from upstream sectors (and vice versa), impacts may be double-counted by both direct and indirect footprints. The duplication part of the equation corrects for this. Based on the sectoral footprint, we estimate company footprint by allocating each company's revenue across sectors and countries in the MRIO table. We then partially extract the corresponding outputs from the MRIO model that match the country-sector combinations in each company's revenue profile, allowing us to quantify its associated climate and biodiversity footprints. It is worth noting that company-level footprint estimates represent approximations and may not fully capture each company's unique production processes.

Text Section S4. Portfolio footprint

The company-level footprint intensity is calculated by dividing the company's total footprint (e_{ci}) by its enterprise value including cash ($EVIC_{ci}$). This reflects the footprint per unit of invested capital and better captures the footprint per unit of financial value held by investors. EVIC is calculated as the total company value (market capitalization, preferred equity, minority interest and total debt) plus cash and cash equivalents. That is, EVIC includes market capitalization at fiscal year-end date, preferred stock, minority interest, and total debt. We use the direct and indirect impacts at company level to derive the direct and indirect impacts attributable to the portfolio. To estimate the portfolio footprint, each company's intensity is multiplied by its benchmark weight in the MSCI ACWI (w_{ciMSCI}), which reflects the proportion of the portfolio's investment allocated to that company.

$$Portfolio\ footprint_{MSCI}\ (per\ million\ euro) = \sum_{ci} w_{ciMSCI} \frac{e_{ci}}{EVIC_{ci}} \qquad (7)$$

Table S1. Sector abbreviations

Sector abbreviation	Sector name
AGR	Agriculture, hunting, forestry & fishing
COL	Coal mining
OGM	Oil & gas mining
NFM	Mining of non-ferrous metal ores and concentrates
FDM	Food production-meat
FDP	Food production-plant
DAI	Dairy products
BEV	Beverage
SEA	Seafood
TOB	Tobacco
TXT	Textiles
WEA	Wearing apparel
PAP	Paper products
PUB	Publishing
CHE	Chemical products
RPP	Rubber and plastic products
NMM	Non-metallic mineral products
MET	Metal production
MMP	Manufacture of metal products
MAC	Manufacture of machinery and equipment n.e.c.
OMC	Manufacture of office machinery and computers
EMC	Manufacture of electrical machinery and apparatus n.e.c.
RTC	Manufacture of radio, television and communication equipment and apparatus
MPO	Manufacture of medical, precision and optical instruments, watches and clocks
MOT	Manufacture of motor vehicles, trailers and semi-trailers
TRA	Manufacture of other transport equipment
FUR	Manufacture of furniture; manufacturing n.e.c.
RWS	Recycling of waste and scrap
PEC	Production of electricity by coal
PEH	Production of electricity by hydro
DTE	Distribution and trade of electricity
GAS	Gas manufacture, distribution
WAD	Water distribution
CON	Construction
RMV	Retail trade of motor vehicles
WAR	Wholesale and retail trade
HAR	Hotels and restaurants
LAT	Land transport
WAT	Water transport
AIT	Air transport
POT	Post and telecommunications
FIN	Financial intermediation
INS	Insurance and pension funding
AFI	Activities auxiliary to financial intermediation
REA	Real estate activities
CRA	Computer and related activities
RAD	Research and development
OBA	Other business activities
EDU	Education
HAS	Health and social work
OTS	Other services