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Going beyond carbon: An "Earth system impact" score to better capture corporate and investment impacts on the earth system

Beatrice Crona [a,b,*], Giorgio Parlato [a,**], Steven Lade [b,c], Ingo Fetzer [b], Victor Maus [d,e]

[a] Global Economic Dynamics and the Biosphere Program, Royal Swedish Academy of Sciences, Sweden
[b] Stockholm Resilience Center, Stockholm University, Sweden
[c] Fenner School of Environment & Society, Australian National University, Australia
[d] Institute for Ecological Economics, Vienna University of Economics and Business, Austria
[e] Advancing Systems Analysis Program, International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria

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ABSTRACT

Corporations are responsible for a significant portion of observed impacts on the Earth system, including greenhouse gas (GHG) emissions, but also water extraction, landuse change and other pressures on nature. These nature-related impacts are essential to consider and capture because they have local impacts on a range of ecosystem functions on which companies and economies depend, but they also fundamentally affect our ability to mitigate and adapt to a changing climate. Furthermore, climate, land and water interact and affect each other in various ways, such that climate change can be exacerbated by degraded ecosystems, which in turn are dependent on water.

This paper tests a novel metric developed to capture corporate Earth system impact (ESI) beyond merely direct GHG emissions and explores how such a tool could be used to improve assessments of corporate environmental impacts and support decisions on where to direct public and private investments. We use the mining sector as a test case to illustrate the applicability of the ESI score and examine the impact of the the five largest (by market cap) mining companies in the precious metal mining sector and the top five in the non-precious metal mining sector. We find that many of the mining assets have non-negligible impacts on land and water, and we show that the ESI metric identifies a different set of asset for targeted action than conventional carbon intensity scores would do.

1. Introduction

Human activities have significantly increased carbon emissions over the past few decades, leading to global climate change (IPCC, 2023). In addition, water extraction and landuse change are resulting in aggregated local pressures. Over time, cumulate pressures on ecosystems and their biodiversity threaten to undermine their capacity to take up and store carbon in soil and biomass, or control green and blue water flow (Hellweg et al., 2023; IPBES, 2019; Lade et al., 2020; Pörtner et al., 2021). Corporations are responsible for a significant portion of these observed impacts (Folke et al., 2019).

In spite of these impacts, natural systems continue to play a critical role in mitigating climate change and its effects on humans. Earth's oceans, forests and other terrestrial ecosystems take up around 53% (21 Gt) of the CO_2 emitted into the atmosphere by human activities (Friedlingstein et al., 2022). Consequently, to move rapidly towards the globally set goals of the Paris Agreement it is not sufficient to focus on, measure, and account for carbon emissions alone. We need to also develop more holistic approaches that assess and account for impacts on important regulating biosphere functions, such as natural vegetation cover and hydrological cycling, in turn upheld by natural ecosystems (Steffen et al., 2015). These functions are interlinked – i.e. they interact and affect each other in various ways (Lade et al., 2020). For example, a changing climate leads to changes in rainfall, which in turn affects vegetation and its ability to sequester carbon in biomass and in soils (Gleeson et al., 2020; Keys et al., 2016; Lade et al., 2020). Capturing the interactions between 'sub-systems' of the Earth system (e.g. between climate, land and water) therefore becomes essential. Against this

* Corresponding author.Global Economic Dynamics and the Biosphere Program, Royal Swedish Academy of Sciences, Sweden
** Corresponding author.
E-mail addresses: beatrice.crona@su.se (B. Crona), giorgio.parlato@kva.se (G. Parlato).

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background, it is noteworthy that until recently the sustainable finance and corporate sustainability domain has been almost entirely dominated by a narrow focus on carbon emissions reduction (Crona et al., 2021, TCFD, CDP, Climate Action 100+, SBTi, etc). Only recently has this community recognized the importance of understanding and acting on nature-related risks (e.g. through TNFD, European Commission, SBTN).

Unfortunately, the approaches and frameworks available and used by the corporate and financial community to address sustainability are not currently up for the task (Savasta-Kennedy, 2014; Popescu et al., 2021). For one, sustainability reporting – which is the main source of data allowing any kind of public assessment of corporate environmental impact – has been driven by Environmental, Social and Governance (ESG) factors, where environmental considerations are only seen as relevant for disclosure by firms if these pose a direct financial risk to the companies themselves (Crona et al., 2021; Crona and Sundström, 2023). Impacts caused by companies, but not directly captured by corporate risk management are largely ignored (Crona et al., 2021; Crona and Sundström, 2023; Grewal and Serafeim, 2020; Quigley, 2020; Richardson and Cragg, 2010). Therefore, even when environmental externalities have been an explicit corporate concern, the data used to construct environmental performance measures often do not match the ambition of capturing absolute impact on the environment (Crona and Sundström, 2023). Lack of environmental and sustainability expertise, and limited ability to scrutinize and understand environmental impact data in the rapidly growing ESG industry, investment community and within companies is a contributing reason for this (Schumacher, 2023).

Secondly, corporate sustainability reporting has focused mainly on carbon emissions without regard for corporate impacts on the systems providing a range of ecosystem services (Savasta-Kennedy, 2014). In other words, measures of corporate environmental performance have generally been climate-centric, neglecting to include other nature-related impacts, such as impacts to land and water, to name only two (Popescu et al., 2021). When environmental variables other than carbon emissions are captured – such as under the Carbon Disclosure Project (CDP), the Global Reporting Initiative (GRI), or the more recently launched Science-based Targets for Nature (SBTN) – little, if any, analysis is generally done to capture their interactions.

To do the latter, entails quantifying sub-global interactions between key Earth system components, such as temperature, surface water runoff, and vegetation, and also estimating how these interactions amplify the effects of carbon emissions, water consumption or impacts on land (Lade et al., 2020). Lade et al. (2021) use an integrative method to do this. They develop a prototype metric to capture Earth system impact beyond merely direct GHG emissions, and account for Earth system components other than climate (water and land), as well as the interactions between them. They combine this with an assessment of the current state of land and surface water at regionally aggregated scale (i.e. measuring regional availability) and also distinguish impacts on land and water by region and vegetation type. The result is an Earth system impact score (from hereon referred to as ESI) which represents a tool that could allow corporate and financial actors to relatively easily report a more inclusive and informative measure of their impact on the Earth and climate system. The three data inputs needed to estimate ESI (CO_2 equivalent emissions, water consumption and landuse), are currently included in many existing voluntary reporting initiatives. Indeed, they are the same as underlying data that goes into the many progress indicators stipulated by a growing number of reporting frameworks (Taskforce on Nature-related Financial Disclosures (TNFD), European Sustainability Reporting Standards (ESRS), Global Reporting Initiative (GRI) to name a few)

The Earth system impact (ESI) score can contribute to the growing desire to capture absolute environmental impact through so called absolute environmental sustainability assessment (AESA). While AESA have so far been grounded in life-cycle assessment (LCA) and based on assigned share of environmental carrying capacity (Bjørn et al., 2020), our approach captures the actual interactions between key Earth system processes, such as climate change, freshwater use and land-system change and the consequences of these interactions for the broader Earth and climate system. Compared to approaches based on assigned shares of environmental carrying capacity this represents a major improvement because these interactions can more than double the Earth system impacts depending on the location where a given activity takes place (Lade et al., 2020). As such, the ESI score provides the capacity to estimate the planetary-scale impact activities and could, therefore, support more realistic AESA, informed by estimates from LCA methods. Furthermore, the score aggregates impacts across climate, land and water, scaled by their respective planetary boundaries. This allows statements about both the total 'Earth system impact' as well as the relative contributions of climate, land and water, to be made.

Despite its promises, the ESI score, developed by Lade et al. (2021), has not been tested on empirical data. This paper therefore uses the mining sector as a case to illustrate how a score, such as the ESI, could be used to improve assessments of impact from economic activities, beyond carbon emissions, to also include land-based emissions and the effects of ecosystem change on large-scale moisture recycling and climate. In doing so we show how this could represent a scientific basis for improving prioritization of mitigative action within companies, as well as support for decisions on where to direct public and private investments. In testing the ESI tool, we chose to examine a primary industry because of the direct impact on the environment through resource extraction and landuse. Furthermore, the outputs of primary industries are usually inputs for all other industries, making the primary sector a necessary starting point to calculate the impact of other downstream industries.

We begin with a short description of the key elements of the analysis underlying the proposed score, and describe the approach taken to select companies within the mining sector, and to process data to test the impact assessment tool. Our results illustrate the types of outputs one could expect, and the discussion then focuses on the implementation potential of the tool for companies and investors, recognizing some key limitations and the risks that need to be considered if use was to be scaled up.

2. Methods

2.1. An earth system impact score

Below we briefly summarize the five key elements of the methodology used to develop the score (for a full description, see Lade et al. (2021) and Figure A1).

First, interaction strengths between climate, land, and water are assessed using the dynamical global vegetation model LPJmL (Dynamic Global Vegetation Model with managed Land, Schaphoff et al., 2018). The model's 13 plant functional types are aggregated into five vegetation types (tropical forest, boreal forest, temperate forest, warm climate grasslands, and cool climate grasslands). Four interactions (changes in climate affecting water runoff; changes in climate affecting vegetation cover; changes in vegetation cover affecting climate; and changes in vegetation cover affecting water runoff, Fig. 1) were quantified through multiple LPJmL simulations using different model settings (e.g. comparing the impact of climate change in scenarios with and without human-induced landuse change). These four interactions have a strong empirical basis (Lade et al., 2020) and are thus deemed of high importance for understanding impact on the Earth system on policy-relevant timeframes (decades or shorter). Second, interactions strengths are normalized relative to regional guardrails derived from the planetary boundary framework. Third, a simple feedback model is used to calculate amplification factors, which measure how pressures on climate, land, or water propagate to other parts of the Earth system. The fourth step consists of weighting the amplification factors by the current state of the Earth System, which results in a set of ESI coefficients for climate (globally) and for land and water in each region (Table A1, Appendix A).

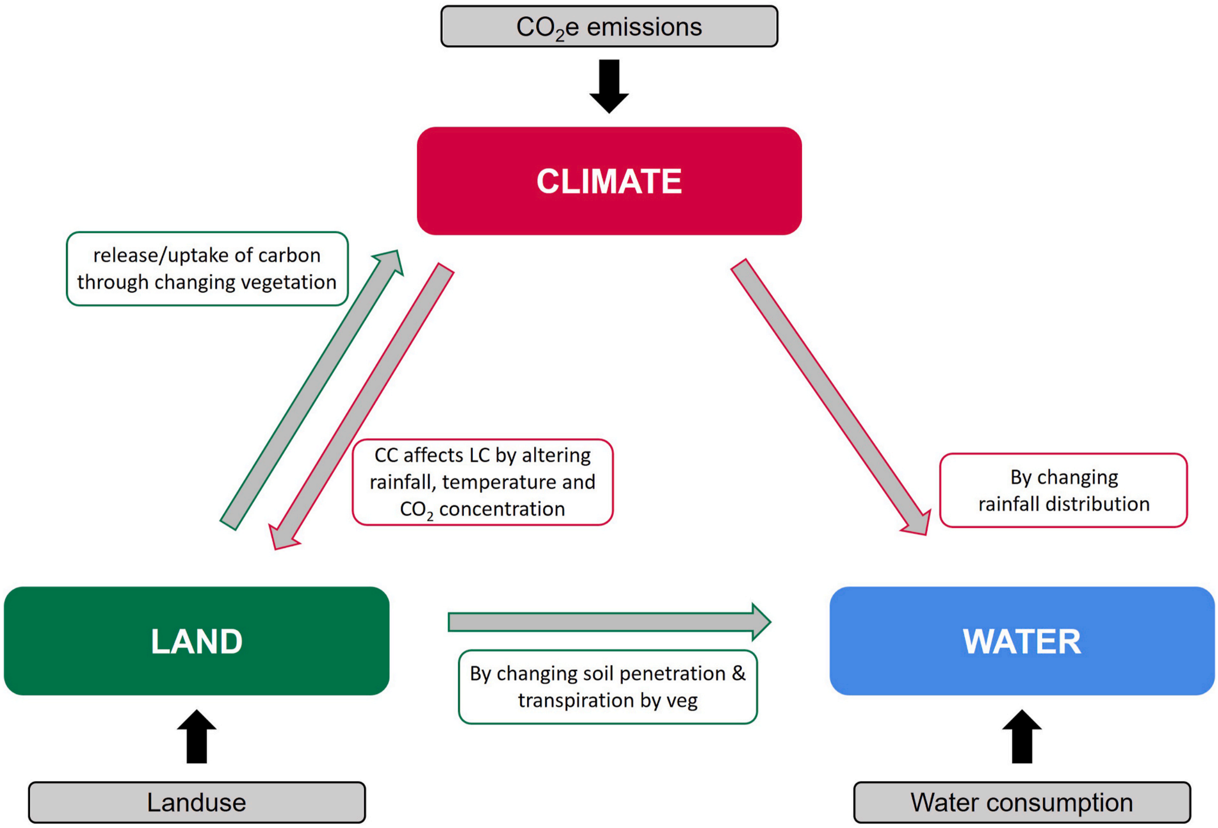

Fig. 1. Earth system interaction assessed by the ESI prototype score. Grey boxes represent the anthropogenic pressures that impact Climate, Land and Water respectively (CO_2e emissions, landuse, and water consumption). These impact drivers represent the data necessary to calculate ESI scores. Grey arrows represent the interactions between Earth System components.

In the fifth and final step, these ESI coefficients are multiplied by emissions, landuse change and water consumption in each region to calculate the Earth System Impact (ESI) score for a given operation or asset (see Figure A1, Appendix A for a schematic overview).

2.2. Using the mining sector to test the applicability of the ESI score

This paper uses the mining sector as a test case for exploring the applicability of the ESI score. The mining sector was chosen for two specific reasons. First and foremost, geo-specifically referenced environmental impacts on water and land from individual mines (also referred to as asset-level throughout this paper) are essential to be able to assess Earth system impact, since the impacts vary as a function of regional availability/scarcity of water and vegetation type and regional landuse change. Such asset-level reporting is not part of most corporate non-financial reporting conventions, but due to increasing scrutiny by regulators and NGOs (Responsible Mining Foundation, 2021), the mining sector is one of few sectors that have begun to more consistently report asset-level carbon dioxide equivalent (from hereon CO_2e) emissions, water consumption and landuse. Second, the mining sector is recognized to have significant environmental (including climatic) impact (Jain et al., 2016; Meißner, 2021; Phillips, 2016).

To test the applicability of the ESI we chose the five largest mining companies (by market capitalization as of February 2022) in the non-precious metal mining sector, and the five largest in precious metal mining, corresponding to NACE codes 07/Mining of metal ores, and 2441/Precious metals production. Selection was done using the ORBIS database (Bureau Van Dijk, 2022, see also Appendix A). Our initial dataset includes the 201 assets owned by these 10 companies; of these, 146 are mining facilities, 33 smelters or refineries, 9 exploration sites, and 13 "other" types of assets, including facilities such as ports, distribution centers and power plants.

2.3. Data and estimation of environmental pressure

Calculating the ESI score requires four types of data for each asset: 1. Geo-coordinates of each facility 2. GWP100 CO_2e emissions (at asset level); 3. Landuse (at asset level); 4. Water consumption (at asset level). We obtain these data from several sources. When available, our primary sources were company reported data gleaned from sustainability and annual reports issued in 2020. Since company reports rarely include asset coordinates, in order to identify mine locations, we relied on companies' websites, publicly available CDP (Carbon Disclosure Project) reports, the Australian Mines Atlas (Geoscience Australia, n.d.), and Google Maps in combination with the database by Maus et al. (2022). When environmental data was not reported by asset (but rather by product group, region, or company-wide), we needed to estimate asset-level pressures (CO_2e emissions, water consumption, and landuse) for each asset of our sample companies. CO_2e emissions and water consumption were estimated using cradle-to-gate LCA estimates and other relevant sources (see Alexander et al., 2021; Farjana et al., 2019; Meißner, 2021; Norgate et al., 2007; Nuss and Eckelman, 2014 and data repository for a complete list of the literature reviewed and utilized in the estimates: https://doi.org/10.7910/DVN/HPYDKW). Landuse was estimated through a dataset on global mining land use (Maus et al., 2022). Detailed methods used to impute asset-level environmental pressures (also referred to as impact drivers) are outlined in Appendix A.

2.4. Calculating and interpreting the ESI score

Calculating the ESI score requires two steps. First, each mine is assigned a vegetation type and region based on its location. Estimation of vegetation types (grassland, boreal, temperate or tropical rain forest and others) is essential because each has a different capacity for evapotranspiration (important for water distribution and flows), carbon uptake (important for carbon storage), and biodiversity (important for mitigating disturbance and maintaining ecological functions). Knowing the location of a mine in relation to vegetation type allows us to estimate the environmental risks and impacts associated with loss of the early 20th century preindustrial baseline vegetation cover. The latter is estimated by LPJmL for any 0.5° cell of the Earth's land surface (Schaphoff et al., 2018). Using historical landcover will penalize mines that were established on land that was previously used by agriculture. However, independently of the state of land at the time of the mine establishment, mining operations prevent the rehabilitation of land to its original state, and thus have a continuous effect through the foregone opportunity to increase the carbon sequestration of that land. The baseline vegetation map includes areas labeled "bare land". These areas can be bare land (deserts, mountain regions or ice-covered areas), but may occasionally include fragile ecosystems that are important for biodiversity and other earth system processes and mining could have impacts there, but such lands are not currently included in the ESI score because LPJmL cannot model these ecosystems. We therefore exclude mines in bare land areas from the analysis (18 assets, of which 16 mines, in our database are located in bare land areas and were excluded).

In the second step we apply the ESI coefficients from Lade et al. (2021) (Table A1 in Appendix A) to each of the impact drivers (emissions, land-cover change, and water extraction) to arrive at an ESI score for each individual driver.

Carbon ESI = emissions (tCO_2e/yr) * CO_2 ESI coefficient (this is the same across regions and vegetation types). The metric of Lade et al. (2021) was specified in total carbon emissions

Water ESI = water consumption (10^3 m^3/yr) * Water ESI coefficient (depending on regional location and vegetation type)

Land ESI = landuse (km^2) * Land ESI coefficient (depending on its location's region and vegetation type)

Total ESI = Carbon ESI + Water ESI + Land ESI

In this way, we not only obtain a score for each asset's total Earth System Impact but can also assess the degree to which individual components (water, land, emissions) contribute to it. A company could assess its overall ESI score by summing the total ESI for all assets. However, since we excluded assets in bare land or those without enough data in this paper, we caution against over-interpreting company-wide ESI results of the companies in this particular sample. For this reason, we also focus our analysis on asset-level impacts.

In terms of interpretation, an ESI score thus represents the Earth system impact of an asset or company relative to environmental guardrails (after weighting by current regional state). In other words, ESI scores are scaled to planetary boundaries. Since any single company will contribute a small fraction of total regional or global impact relative to these boundaries, ESI scores are usually much smaller than 1. This small number, however, does not represent negligible impact.

2.5. ESI intensity

The ESI score estimates absolute environmental impact (*sensu* Bjørn et al., 2017) of certain activities normalized to regional guardrails. While it is essential to track the absolute impact of anthropogenic activities to assess our ability to stay within planetary boundaries, it is important to understand that absolute impact can be driven by the size of a company's operations, obfuscating other factors, such as efficiency of production. There can therefore be a value in using complementary measures of intensity, that indicate impact relative to production, revenues, or capital invested. Such intensity measures "control" for the effect of size on environmental impact, emphasizing more the effect of corporate practices, innovation, and in the case of ESI, the location of impact. We calculate ESI intensity measures by dividing the total ESI of each asset by the total revenue, using reported revenue when they can be traced to an individual asset. When asset-level figures are not disclosed, or not clear, we estimate revenues by multiplying the average realized price by the volume produced (when the realized price is not reported, we use the average commodity price in 2020 from a relevant source). We discuss any complications with estimating asset-level revenues for mining companies in Appendix A.

3. Results

3.1. Emissions, landuse and water consumption are necessary, but not sufficient, to assess corporate earth system impact

Our findings indicate that practices in many regions are associated with an impact that goes beyond what one would expect from looking only at de facto volume of water consumption or land area appropriated. Accounting for interactions between components of the Earth system, such as land and water (in addition to CO_2e emissions), along with considerations of the current state of a particular component in relation to estimated guardrails and regional availability, captures a fuller understanding of the impacts of corporate activities on the Earth system. This influences the assessment of environmental impact such that mines with relatively low water consumption can still incur relatively large impacts on the Earth system (Fig. 2). Mines located in vegetation types classified as 'warm climate grasslands' in North America, 'cool climate grasslands' in Africa and South America, and 'temperate forests' in Australia have a particularly high Earth system impact from water consumption (Fig. 2A). Mines in 'cool climate grasslands' in Africa, 'warm climate grasslands' in Australia and North America, and in 'tropical forests' in Asia, South America and Africa, have relatively larger impact on the planet stemming from their landuse (Fig. 2B).

This result underscores one of the strengths of this tool, namely its ability to assess globally relevant impact of local economic activities. However, it is important to note that this does not mean that the ESI measure can replace assessments of local impacts. There are multiple locally important environmental impacts (such as pollution, biodiversity loss, or introduction of invasive species) that may be critical for site-specific ecosystem services that support both companies and the wider communities in which they are embedded, but which may not have immediately global effects.

3.2. Carbon, land or water? Contributions to total earth system impact vary across localities

Even for mines with similar total ESI, water, land and greenhouse gases contribute differently to the total impact, depending on mine location (Fig. 3). The individual contribution of each of the three impact drivers to total ESI is shown by color. The standard deviations of the relative contributions of each of climate, land and water to ESI across assets are more than 20% showing a relatively big range (Table 1; see Figure A2 in Appendix A for detailed distribution plots for each ESI component). These varying contributions are the result of how location and the different ways in which disturbance to vegetation types, and the regions in which they are found, contribute to overall impact on the Earth system (Fig. 2).

In 51% of the mines analyzed, carbon is the main contributing component, but for 40%, landuse is the factor that most contributes to total impact on the Earth system (as measured here) (Table 1). This illustrates the importance of accounting, in addition to CO_2e emissions, for other forms of impacts and their interactions. Water is the main contributing factor in fewer assets in this particular dataset. However, this is not an indication of a low water imprint by the mining sector as a whole, but simply a reflection of the mining companies included in this

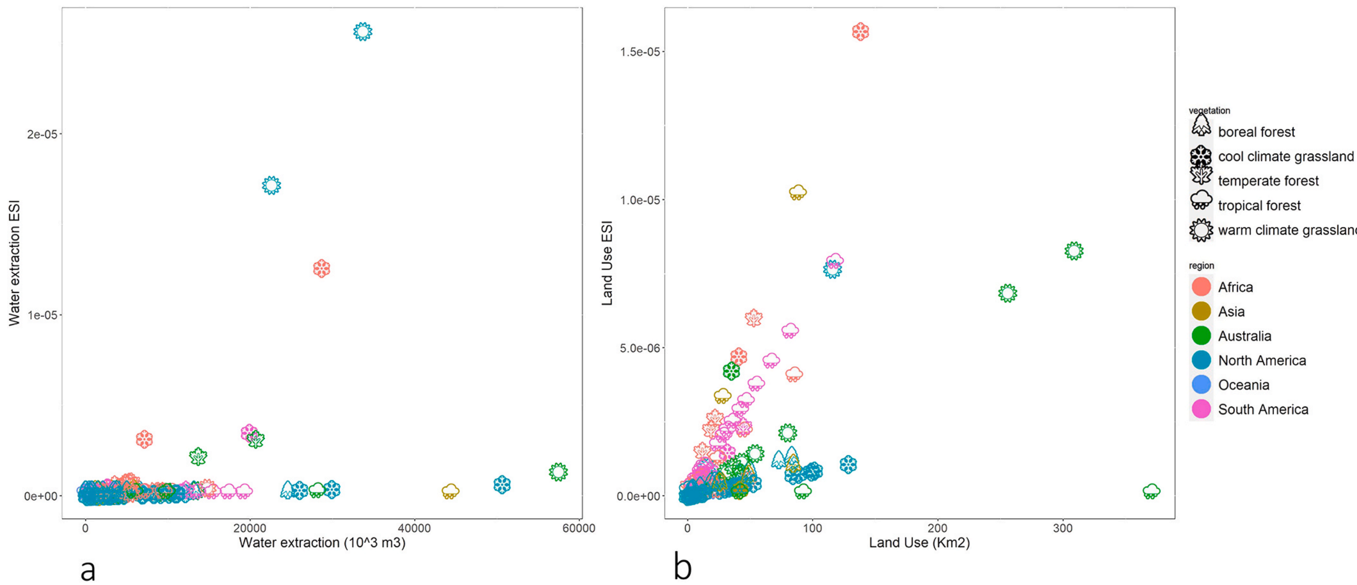

Fig. 2. Relationship between conventional measures of (A) water consumption (10^3 m^3) and (B) landuse (km^2) compared to a water consumption and landuse impact measure that accounts for interactions between Earth system components (carbon, land, water).

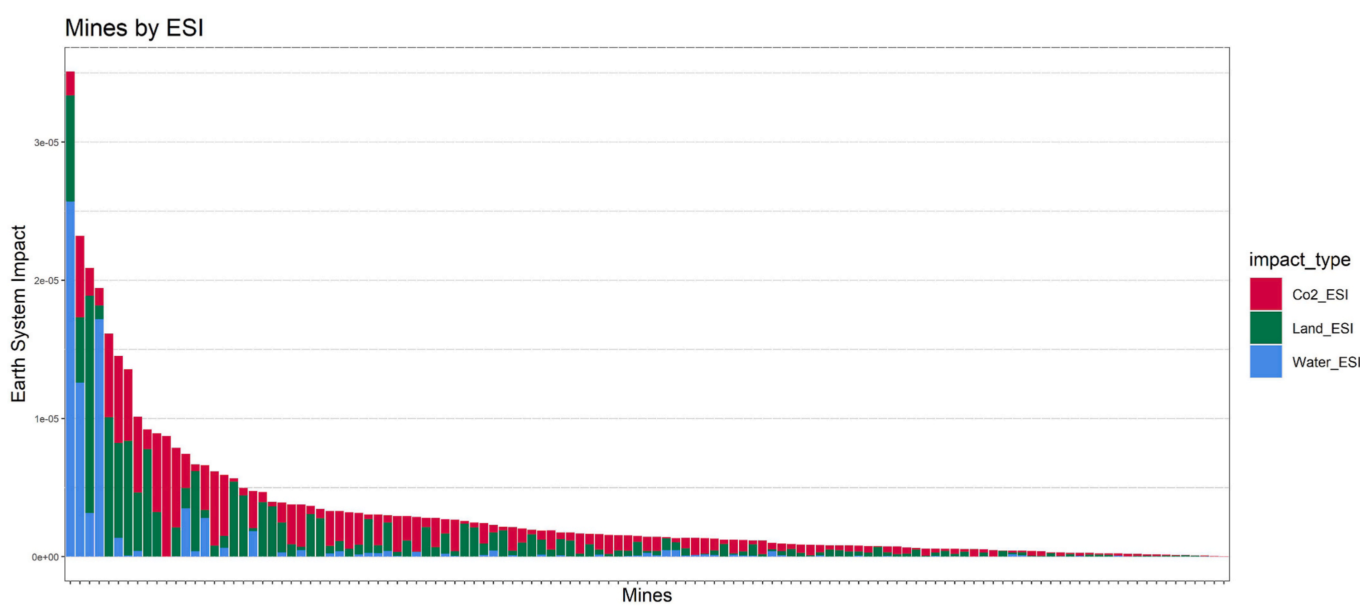

Fig. 3. Total Earth System Impact for all mines examined (n = 121). The contribution of each component (carbon, water, land) to total ESI is shown by color. Mines are ordered along the x-axis by total ESI. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

analysis, in which fewer assets were located in water scarce regions.

The low water-related Earth system impact is in part also a result of the boundary conditions used in the prototype tool. Boundary conditions for water are based on the updated version of the water boundary (Steffen et al., 2015), but this boundary has been critiqued for presenting an overly optimistic view of water stress, as many places around the world are currently extracting more water than would be considered "safe" from a planetary boundary perspective. Additional work, such as Gerten et al. (2013); Porkka et al. (2022); Wang-Erlandsson et al. (2022), and the recently released Earth System Boundaries (Rockström et al., 2023), give stricter boundaries on water use. In a future version of the prototype score incorporating the updated boundary, water's contribution to ESI would therefore likely increase substantially for economic activities in several regions.

3.3. Shedding light on the limitations of carbon intensity measures

Carbon, or emissions, intensity is a term used to denote calculations of the amount of CO_2e emitted per volume of product produced, or per revenue generated, by a company. It has become one of the most common measures used by companies to report on their environmental impact and is therefore also found among the variables used by ESG rating companies to rank companies for financial investors. Consequently, reporting on the carbon intensity of investment funds is now a growing practice among investors worldwide. One reason for the popularity of carbon intensity as a measure of impact is that it allows for the comparison of companies or investment funds, since emissions are normalized by a chosen denominator (like production volume or value, or the value of the assets under management).

Table 1
Contribution by the three impact drivers (CO_2e emissions, landuse and water consumption) to total ESI score across mines in our sample. The top two rows show mean and standard deviation of contributions of each impact driver (see Appendix A; Figure A2 for detailed plots for each ESI component). The bottom panel shows the percentage of assets where emissions, landuse and water consumption (respectively) has the largest contribution to total ESI score by that same asset. We provide these statistics for mines only, as well as for all assets, including smelters and refineries. Since the majority of the impact of smelters and refineries stems from CO_2e emissions, the emissions contribution to total ESI increases when they are included.

	CO_2e emissions	Water consumption	Landuse
mean	51.3%	8.5%	40.3%
standard deviation	27.5%	14.5%	28.6%
% largest contributor (mines only)	55.4%	4.1%	39.7%
% largest contributor (all assets)	59.6%	3.5%	36.2%

Just like CO_2 emission can be turned into an intensity measure, so too can ESI. CO_2 intensity measures are often used to identify assets that have a high impact and that should be prioritized for various improvement measures. This can be within a company, where targets are set to improve overall performance and where intensity measures are used to identify hotspots in need of action. CO_2 intensity is also often used by institutional investors to identify high-emitting companies in their portfolio with whom they want to prioritize engagement, or by fund managers who decide on what companies to include or exclude in their funds based on carbon intensity.

To demonstrate the added value and additional understanding of Earth system impacts provided by ESI intensity scores, Fig. 4 superimposes the ESI intensity plot on a conventional plot ordering mines along decreasing CO_2e intensity (black line). Visual inspection shows that using CO_2 intensity to rank mines as a means to identify highly impactful operations risks misrepresenting which those highly impactful mines are. Indeed, we see that the carbon intensity curve drops fairly quickly, yet a number of mines ranked among the medium to lowest emitters can be some of the most harmful from an Earth System perspective. These are the mines that have non-negligible impacts from their water and landuse and therefore, in addition to their CO_2e emissions, make them worthy of particular scrutiny. These results illustrate clearly that when we include the interactions between emissions, landuse, and water consumption – as well as the regional availability of each, and the estimated planetary guardrail for safe operating space – a different set of companies appear as important for prioritization than what only carbon intensity measures can capture. Relying on CO_2e emissions alone will therefore significantly misrepresent global environmental impact.

4. Discussion

The ESI score tested here is a prototype score developed to go beyond carbon and capture a wider set of environmental dimensions, operating at different scales, that have bearing on Earth system stability. Specifically, these dimensions represent two key planetary scale processes: water circulation and changing landuse, which both interact with climate change in ways that can amplify global climate change. Extraction of water and landuse also affect global freshwater cycling and functioning of terrestrial ecosystems, which in turn affect humans through our reliance on those ecosystems (IPBES, 2019). The ESI score is

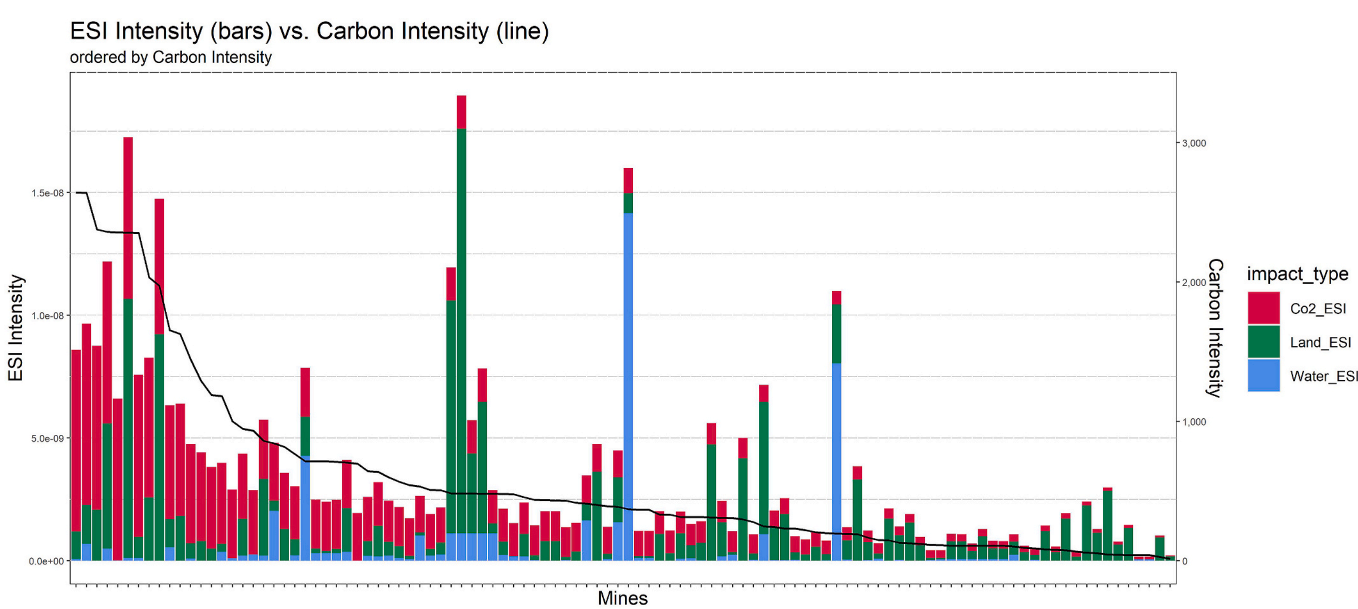

Fig. 4. Earth System Impact intensity compared to CO_2 intensity for mining assets with revenues above $100M in our sample (n = 106). For each mine, the ESI score is also broken down to indicate the individual contribution of CO_2 emissions, landuse and water consumption to the total ESI score. Superimposed on the ESI intensity plot is the CO_2 intensity measure for each mine (black line), and mines are plotted (from left to right) according to their carbon intensity score.

also designed to account for the fact that the various vegetation types have different capacity to store carbon and affect recirculation of water. Where on the planet an economic activity takes place therefore matters for its overall impact on the interconnected global processes of moisture recycling, landcover and climate. It also means that mitigation of pressures needs to be done at different scales: while impacts on the atmosphere (through GHG emission) is relevant to address at a planetary scale, water use and moisture recycling, and land-cover change, must be assessed at regional scales (Gleeson et al., 2020; Wang-Erlandsson et al., 2022). The fact that processes interact across scales means we need to find ways to capture these impacts both as individual processes (e.g. moisture recycling resulting in water availability; or landcover change) and their interactions. The ESI score presented and tested in this paper is a first step in this direction.

We see multiple ways in which such a score could be used by both public and private sectors, and we outline these below. However, a key barrier to its use is that non-financial disclosures tend to be reported at the company level, while the input data required by the ESI must be georeferenced at the level of individual assets. As explained above, this is because the ESI score - and any meaningful assessment of interactions between climate, water and land – needs to account for the location of environmental impacts. While asset-level reporting may seem onerous, we argue that in comparison to most current and emerging environmental disclosure standards, the inputs required to use the score are few, clear, and already relatively easily reportable for many companies; geocoordinates of assets; CO_2e emissions; landuse; and water consumption. Keeping in mind these current obstacles to widespread implementation of ESI, below we outline a number of plausible uses, for companies and investors. We discuss the opportunities and drawbacks with each and finish by highlighting key areas in need of further development.

4.1. Implementation opportunities

4.1.1. Footprinting tool or target setting?

The ESI was developed over several methodological steps, where each step adds a layer of complexity. The "full" version of the score used in this paper is the most appropriate to assess and compare the Earth system impact of assets or companies, for example when making investment decisions. It is akin to a footprinting tool and because the score takes account of the current Earth system state it means corporate activities in already degraded regions are penalized. Naturally, companies could set their individual targets for reducing the ESI of their operations over time.

It would also be possible to use a less complex version of the ESI to set targets. In this simpler version of the score, water consumption, landuse and CO2e emissions from corporate activities are scaled relative to regional (or global, in the case of CO2e emissions) guardrails, without weighting by the current states of the Earth system in these regions. Such an ESI score would directly represent the contribution of a company's activities towards transgsressing these guardrails. Corporate targets for reducing ESI could therefore be readily set and progress evaluated against guardrails, for example in an evaluation process similar to science-based targets (SBTi, SBTN, see Science Based Targets Network, 2023). Omitting Earth system interactions from the score would further simplify the process of target-setting, since including interactions means that achieving targets in one region depends on activities in other regions, but would neglect important impacts arising from these interactions.

4.1.2. Earth system impact assessment of planned projects and investments

With the work on the EU Taxonomy Regulation and the EU Green Bond Standard, the European Union has led a massive effort to encourage flows of investments, through loans, equity investments and public spending, toward sustainable activities. Some of the needed investment will have to be covered by public spending while private finance will also have to contribute to closing the funding gap (Deutza et al., 2020; European Commission, 2020; "European green bond standard," n.d.; TEG European Commission, 2020). In the process of assessing and prioritizing projects for financing, ESI could be used by both public and private actors, such as corporate and development banks.

Regardless of public investments, lending institutions could benefit from the use of an ESI score to assess the potential environmental impact of their portfolios, and the tool could also serve as a means to identify clients with specific needs to transition to less impactful operations in certain regions. The concerns regarding data availability mentioned above would be less relevant, as new project developments would likely have estimated the location and magnitude of environmental pressures in the pre-assessment phase. Thus, ESI could be effectively used to improve sustainability assessments of primary market investment decisions (c.f. Quigley, 2019).

4.1.3. Assessing impacts of company assets or investment portfolios

For companies wanting to reduce negative environmental impact across their operations, the ESI score could be used to identify which localities have the biggest integrated Earth system impact. Furthermore, the ability to calculate the disaggregated impact of each asset by Earth system domain/component positions it as a tool to help companies prioritize which environmental impacts are most pressing to address in a particular site. Similar to (and in collaboration with) lending institutions, companies could use ESI to estimate and compare the impacts of potential new projects, and to assess the environmental impact of implementing transition technologies or processes that impact several Earth System components. For example, carbon capture and storage technology may reduce a power plant's CO_2e emissions but increase its water usage (Macknick et al., 2012; Rosa et al., 2020; Webster et al., 2013), and implementing such new technology could have both negative and positive impact on the Earth System, depending on the plant's location. Many companies nowadays embrace science-based target setting to guide their environmental strategies. As noted above, a less complex version of ESI can be used for this purpose, similar to existing science-based targets.

Many large asset owners, such as pension funds, insurance companies, university endowments, and sovereign wealth funds, cannot hedge against environmental externalities. They own assets (i.e. shares of companies) in almost all markets and sectors (Hawley and Williams, 2007). This is part of their investment model and has given rise to the term 'universal' owner (ibid). Because of this investment model, they cannot hedge against externalities and as such their long-term performance is fundamentally coupled with the health of the system as a whole (Quigley, 2019). For these investors, there is thus an interest in mitigating systemic risks, such as the amplifying effects of aggregate emissions and pressures on land and water (ibid). Yet as noted above, current mainstream corporate reporting means they cannot assess how their investments are contributing to such systemic risks. The Climate Action 100+ initiative gathers a large coalition of investors to target the 100+ largest corporate GHG emitters in the world to ensure they take necessary action on climate change. The recently initiated Nature Action 100 is modeled on this approach, but while CA100+ relied on reported and estimated CO_2 emissions to identify the biggest emitters among the MSCI All Country World Index (largely from CDP), the lack of asset level data makes a similar analysis difficult for nature-related impacts. However, when and if such disclosures become available for a larger number of companies, universal owners could use ESI to similarly identify companies in their portfolios with high impact, to prioritize targeted engagement. In the meantime, investors with an ambition to understand and reduce their impact on the Earth and climate system, and practicing 'active ownership' (Dimson et al., 2015; Sjöström, 2020), could demand companies to disclose a minimum of three variables (water consumption, landuse, and GHG emissions), by asset. This would allow for the calculation of ESI scores of individual company assets and identification of which Earth system domains (carbon, water, and land) are under most pressure from a particular company or asset. This could serve as valuable support for targeted and tactical board engagement around strategies to prioritize and reduce the overall impact (Quigley, 2019).

4.1.4. Assessment of environmental impact: the role of current and emerging reporting frameworks

Multiple initiatives are underway in the EU, and more globally, to begin to account for corporate and financial environmental impacts. That is, impacts that go beyond CO_2e emissions. Examples include the work by the Taskforce on Nature-related Financial Disclosures (TNFD), the International Sustainability Standards Board (ISSB), the Global reporting Initiative (GRI), the Science-Based Targets Initiative for Nature (SBTN), the Carbon Disclosure Project (CDP) and the more recent and mandatory reporting requirements released by the EU Commission in the form of the draft European Sustainability Reporting Standards (ESRS). There are also a number of other initiatives working to develop best practices or guidelines for companies and investors to report on and reduce their environmental harm (e.g. Finance for Biodiversity pledge). While it is encouraging to see the growing recognition of environmental impacts on the corporate and financial policy agenda, many reporting initiatives ask companies to report on targets set, often through untransparently calculated indicators of progress towards those targets, and policies in place, but rarely specific KPIs to implement them (see e.g., EFRAG, 2022; GRI, 2022; SBTi). This is developing into a rapidly increasing reporting burden, some of which may not directly improve our capacity to gage and curb environmental harm. Yet the ESI tool, in its current form, requires only a limited number of geo-specific data categories, such as water consumption and landuse, as well as emissions, but can significantly improve our capacity to evaluate global impact of local corporate activities. Along with a growing number of scientifically grounded and transparent analytical tools (see e.g. the global InVest model; Natural Capital Project, 2022), ESI thus offers more sophisticated analytical potential without adding to the reporting burden, and can in fact help guide the development of reporting standards by illustrating what is important for organisations to disclose. This should be complemented with additional examination of what are essential environmental corporate impacts that need to be disclosed (c.f. Science Based Targets Network, 2023; Wassénius et al., 2023).

4.1.5. Remaining challenges and areas of future improvement

We present a number of opportunities and plausible use cases of the ESI score, yet at the time of writing not all of them would be feasible. We have already noted that lack of appropriate disclosures is a key barrier. However, even if disclosures of asset level impacts were available, and ESI could be calculated across companies in land-based extractive industries (e.g. mining, agriculture, forestry), a comprehensive impact assessment of companies in downstream segments will require transparency and traceability to trace the impact of inputs used (e.g. Calvão and Archer, 2021; Gardner et al., 2019; Renier et al., 2023). The score presented here cannot address this challenge For it to be widely applicable to all types of industries, it would also rely on the development of methods to trace and assign "upstream scope 3" impact to companies in downstream industries. The exclusion of indirect impacts is a limitation of the current study and represents an important challenge and next step to address in future studies. Estimates for the environmental pressures caused by downstream activities can be calculated using methodologies such as input-output life cycle assessment (IOLCA). This was recently used to estimate Scope 3 emissions of 11,275 companies (Popescu et al., 2023). However, doing so relies on sector averages, thus it precludes insights about a specific company's impact (Hellweg et al., 2023; Popescu et al., 2021). While the IOLCA's approach can capture broad impacts of a sector or portfolio based on average impact estimates, they cannot help in identifying the best or worst performing companies within a sector. The ESI metric, on the other hand, is a company-centric metric, and better suited to provide insights about individual companies, thus providing investors with a more nuanced decision-making tool to engage with companies and identify the most harmful impacts on the Earth System that should be prioritized. Naturally, when data is available (or can be imputed) for all portfolio companies, the overall portfolio impact can also be assessed. This can be particularly important as more awareness is raised about the role of universal owners in reducing systemic risk by actively engaging with companies that have substantial environmental impact (Sjöström, 2020).

We also want to flag that in the mining industry, there are frequently legacy assets in the form of retired mines. When such mines have been retired, but not rehabilitated, they technically still constitute an impact on land, even though they may not be consuming water or emitting GHG. However, corporate reporting overwhelmingly focuses on operational assets, thus omitting our ability to assess the impact of retired mines. Similar issues of legacy assets with lingering environmental impacts could be an issue in other sectors as well, and is a topic that needs further investigation. Finally, some mining companies own shares in mines they do not directly operate. Sustainability reports, from which data is derived normally, cover only the environmental impact of assets directly operated by the company. In other words, the impacts of assets owned but not operated by a company are not included in our data. Companies could thus intentionally avoid responsibility for the environmental impact of some of their assets, by assigning another company to manage them. For the purpose of our analysis we do not delve further into this, but the attribution of impact responsibility under such joint ownership would matter if the tool was applied across the entire mining sector, or across other sectors – and a method would need to be devised to avoid missing information or double counting.

4.2. Technical limitations

While the ESI score could be seen as an improvement to current practices to assess environmental impact, it is important to emphasize its limitations, and the need to integrate its use with other measures. First, the ESI is regionally aggregated and focuses on impacts at a planetary scale. It therefore does not replace assessments of local environmental impacts, such as pollution or biodiversity impacts. Second, the score currently captures three Earth system components, and four of their interactions. Further modelling work could integrate more planetary boundaries, more interactions among them, and more detailed representations of Earth system components (e.g. accounting for green water or GHG gases other than carbon). The score can also likely be linked to current developments to capture spatially explicit impacts of human activity on biodiversity and ecosystem services (e.g. Chaplin-Kramer et al., 2019). A third limitation is that since the score does not currently account for the potential effect of tipping points in accelerating environmental change, it might underestimate the impact in regions close to tipping. A current limitation that we hope to overcome in the future is that the metric works by scaling the impacts of carbon emissions against the planetary boundary, where we use the Steffen et al. (2015) figures of 350 ppm. However, companies generally report their emissions in CO_2e – a measure that expresses the impact of each different greenhouse gas in terms of the amount of CO_2 that would create the same amount of warming. Using CO_2e in the metric works for all interactions captured in ESI except for the effect of increasing temperature on land cover through photosynthesis, where only CO_2 is relevant. In other words, all GHG gases contribute to all interactions except for temperature impacts on photosynthesis. Since a majority of companies only report CO_2e values, we have nonetheless used these in our estimations of ESI. However, we do note that this could lead to some overestimation of the landcover impact for companies whose emissions have a larger component of non-CO_2 emissions, such as coal mining companies. Finally, in order to get the most accurate results, it is necessary to periodically update the underlying data upon which the score was built. As mentioned, an updated planetary boundary for green water was recently published (Wang-Erlandsson et al., 2022) and has not yet been incorporated into the score. The data used to calibrate the 'current state of the Earth System' in the score outlined here refers to 2013 and would need to be regularly updated.

CRediT authorship contribution statement

Beatrice Crona: Conceptualization, Methodology, Writing – original draft, Supervision, Project administration, Funding acquisition. **Giorgio Parlato:** Methodology, Data curation, Writing – original draft. **Steven Lade:** Methodology, Writing – original draft. **Ingo Fetzer:** Methodology, Writing – original draft. **Victor Maus:** Methodology.

Declaration of competing interest

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Data availability

all data available via Harvard Dataverse, link provided in manuscript

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Appendix A. Supplementary data

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