A prototype Earth system impact metric that accounts for cross-scale interactions

Steven J Lade$^{1,2}$, Ingo Fetzer$^3$, Sarah E Cornell$^1$ and Beatrice Crona$^{1,3}$

$^1$ Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden
$^2$ Fenner School of Environment and Society, Australian National University, Canberra, Australia
$^3$ Global Economic Dynamics and the Biosphere, Royal Swedish Academy of Sciences, Stockholm, Sweden

E-mail: steven.lade@su.se

Keywords: human pressures, feedbacks, impact metric, Earth system interactions, land cover change

Supplementary material for this article is available online

Abstract

Human activities are disrupting the Earth system’s biophysical processes, which underlie human wellbeing. The planetary boundary framework sets ‘safe’ global limits on these pressures, but a sub-global assessment of these pressures, their interactions and subsequent systemic effects is needed to enable corporate and public entities to assess the systemic environmental impacts of their decisions. Here, we developed a prototype Earth system impact metric that is savvy to Earth system interactions. First, we quantified sub-global interactions between climate change, surface water runoff, and vegetation cover using the global dynamic vegetation model LPJmL (Lund-Potsdam-Jena managed Land). Second, we used a feedback model to study how these interactions amplify environmental impacts. We found, for example, that interactions more than double the Earth system impacts of deforestation in some tropical forests. Finally, we combined these amplification factors with an assessment of the current state of the Earth system to create a prototype Earth system impact metric. We envision that future versions of our prototype metric will allow corporate and public actors to better assess the systemic environmental impacts of their decisions. Our ambition is that these results catalyse further scientific work to extend and improve this metric, as well as action by investors, companies, cities, and governments to deliver sustainable outcomes across the private and public sectors.

1. Introduction

Global anthropogenic modification of Earth system processes has increased exponentially during recent decades (Steffen et al 2015a). The extent of human disruptions to several components of the Earth system, as characterised by the planetary boundary framework, has exceeded the limits of a scientifically determined ‘safe operating space’ and threatens the natural capacity of the planet to support human wellbeing (Steffen et al 2015b). Once globally aggregated interactions between Earth system processes are considered, the future safe operating space is reduced even further (Lade et al 2020). For example, carbon released by deforestation affects global climate; climate changes affect water resources and ecosystems in partially predictable ways, often in locations distant from the original pressure (Liu et al 2013). While interactions between these pressures on the Earth system have been systematically assessed at the global scale (Lade et al 2020), a sub-global approach is needed to address the spatial nature of pressures on the Earth system and their resultant impacts.

A sub-global assessment of Earth system interactions is also needed to respond to rising concerns among a wide range of corporate and financial stakeholders (Alpro 2018, Cranston and Steffen 2019, World Economic Forum 2019) about global environmental risks (Keys et al 2019). Some prominent initiatives and organizations have begun to include additional environmental dimensions to assess environmental impacts of corporate and financial actors. For example, the Sustainability Accounting Standards Board now includes water withdrawal, use of fertilizers and qualitative descriptions of land-use management strategies (SASB 2015), and the Global
Reporting Initiative outlines corporate reporting requirements that, in addition to emissions, include water withdrawal, effluents, waste and biodiversity. Nonetheless, greenhouse gas emissions reduction still dominates discussions and measurements, in both research and practice relating to corporate sustainability and sustainable investments (Crona et al 2021).

Furthermore, environmental impact metrics usually neither (a) account for Earth system interactions that could amplify human pressures on the Earth system nor (b) compare the magnitudes of pressures to scientifically established Earth system reference points such as the planetary boundaries, with the exception of targets on greenhouse gas emissions for keeping climate change below 2 °C or 1.5 °C this century. Neglecting these interactions may lead to an underestimation of the impact imposed by economic activities and flawed estimates of the long-term sustainability of investments. It is crucial to give businesses and their investors the tools to understand to what extent their activities disrupt the Earth system, which is only possible by referencing impacts to scientifically established targets or limits.

Here, we take a first step towards addressing these gaps by estimating cross-scale Earth system interactions and using these results to construct a prototype Earth system metric. First, we used the dynamical global vegetation model LPJmL (Lund-Potsdam-Jena managed Land, Schaphoff et al 2018a) to assess interactions involving three major Earth system components: climate, land and water, measured by changes in atmospheric carbon dioxide concentration, vegetation cover and surface water runoff, respectively. We chose these three components in recognition of the central roles of climate and the biosphere in the Earth system (Steffen et al 2015b), noting that changes in vegetation cover and water flows are among the most important mediators of human pressure on the terrestrial biosphere. Additionally, carbon emissions, land clearing and water extraction are among the most readily measured and widespread pressures on the Earth system. We assessed interactions sub-globally, over regions defined by the aggregation of vegetation types in each continent.

Second, we used a simple feedback model to estimate amplification factors, which we define as the extent to which interactions amplify pressures on different components of the Earth system. In calculating these amplification factors, we accounted for guardrails derived from the planetary boundary framework for the safe level of impacts on these Earth system components. We use the term ‘guardrail’ (Yohe and Toth 2000) to distinguish our regional-scale limits from the planetary boundaries, which set ‘safe’ global limits on perturbations that maintain the Earth system within a Holocene-like state (Steffen et al 2015b).

Third, we used LPJmL to assess the current states of our land and water variables at regionally aggregated scales. Additional stress to regions of the planet that are already suffering from severe environmental impact could trigger irreversible changes with effects that play out across scales (IPBES 2019). Metrics therefore need to be grounded in a spatially resolved assessment of the current state of the Earth system.

Finally, we developed a prototype metric for the impacts of human pressures on the Earth system by combining the amplification factors with the current state of the Earth system. This metric assesses impacts on the Earth system, in response to human pressures, accounting for propagation of pressures through Earth system interactions, with respect to guardrails, at sub-global scales.

The Earth system metric we present is a prototype based on an important but small subset of Earth system interactions, estimated using one dynamic global vegetation model. Our goal is to stimulate further research and refinement on such metrics, for example incorporating additional interactions and additional Earth system components and investigating the variability across multiple Earth system models. We envision that future versions of this metric will enable actors such as businesses and investors to make decisions that are ‘Earth system savvy’ to the global environmental risks emerging from their pressures on the Earth system, in the same way that financially ‘savvy’ decisions account for financial risks.

2. Methods

Our approach consisted of two main steps (figure 1(a)): (a) using the spatially-resolved dynamical global vegetation model LPJmL (Schaphoff et al 2018a) to estimate the strengths of cross-scale interactions between climate, land and water; and (b) using these interaction strengths in a simple feedback model to calculate measures that assess the consequences of these interactions for the Earth system, specifically an amplification factor and an Earth system impact metric. Detailed descriptions of our calculations are available in the supplementary methods (available online at stacks.iop.org/ERL/16/115005/mmedia). We use the terms ‘pressure’ and ‘state’ in line with the (drivers, pressures, states, impacts, responses) framework (Patrício et al 2016) and reserve the term ‘impact’ for the cumulative change in state once all feedbacks, themselves triggered by an initial change in state, have played out.

2.1. Estimating interaction strengths

We used LPJmL to assess four cross-scale Earth system interactions (figure 1(b)): changes in climate affecting runoff, for example through changing rainfall distributions; changes in climate (including changes in atmospheric carbon dioxide concentrations) affecting vegetation cover, for example through changing temperature and rainfall; changing vegetation cover affecting climate, through release or uptake of carbon;
and changing vegetation cover affecting water runoff, for example through changing soil penetration.

We used LPJmL (version 4.0.002) since it is one of the most advanced dynamic global vegetation models, including detailed descriptions of hydrology, land use and agriculture (Schaphoff et al 2018a), and has been tested against a wide range of observations (Schaphoff et al 2018b). It also offers the capability to switch on and off human land use change, which is critical for our analysis and not widely available in model intercomparisons such as ISI-MIP (Inter-Sectoral Impact Model Intercomparison Project, Warszawski et al 2014).

We chose these four interactions since they each have a strong empirical basis (see review by Lade et al 2020) and lead to impacts on policy-relevant time scales of decades or shorter. Other interactions between these variables (Lade et al 2020), such as deforestation changing land surface albedo and affecting climate, would require other models than LPJmL to characterize them. Other features of the water cycle such as groundwater and green water (Gleeson et al 2020) or ecosystem composition such as biodiversity (Purvis 2020) also important in Earth system functioning, but operate on longer time scales or are difficult to quantitatively characterize using LPJmL.

To calculate the effects of vegetation cover change on climate and water runoff, we compared LPJmL results (a) with and (b) without human-induced land system change (table 1, supplementary methods) for the same climate drivers. Similar approaches are used to estimate interactions within the carbon cycle (Friedlingstein et al 2006, Arora et al 2013, Lade et al 2018). To calculate the effects of climate change on vegetation cover and water runoff, we examined LPJmL results over time with human-induced land system change turned off (table 1 and supplementary methods).

For historical interaction strengths we analysed LPJmL output driven by re-analysis data from CRU TS (Climate Research Unit gridded Time Series) (Harris et al 2014, Trenberth et al 2014). The CRU TS is a 0.5° resolution gridded dataset contain monthly time series of precipitation, daily maximum and minimum temperatures, cloud cover, and other variables covering Earth’s land areas for 1901–2013 based on analysis of over 4000 individual weather station records. We also analysed LPJmL runs driven by representative concentration pathway (RCP) climate scenarios RCP 2.6, 4.5, 6.0 and 8.5 from multiple climate models (CanESM2, GFDL-CM3, GFDL-ESM2G, HadGEM2-AO, MIROC-ESM, NorESM1-ME) with monthly inputs on a 0.5° resolution over the period 1901–2099. We selected those six climate model outputs as they are among the most reputable and well-known models and represent a spectrum of models from different model families.

We aggregated our results into five vegetation types (tropical forest; temperate forest; boreal forest; cool climate C3 grasses found in temperate grassland and arctic tundra; and warm climate C4 grasses, found in savannah) within each of six
Table 1. LPJmL runs used for estimating interaction strengths. These runs and interaction estimations were repeated for historical climate and a range of future climate scenarios generated by a range of climate models (see text for choice of models). A mathematical description of each calculation is available in supplementary methods.

| Interaction                                      | Simulation runs                                                                 | Calculation                                                                 |
|--------------------------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Climate change → surface water runoff            | Without human-driven land use change                                         | Slope of runoff vs atmospheric CO₂                                           |
| Climate change → vegetation cover                | Without human-driven land use change                                         | Slope of vegetation area vs atmospheric CO₂                                  |
| Vegetation cover → surface water runoff          | (a) With and (b) without human-driven land use change. Same climate driver in both runs. | Difference in runoff between ends of simulations (a) and (b) divided by difference in vegetation area between end of simulations (a) and (b). |
| Vegetation cover → climate change                | (a) With and (b) without human-driven land use change. Same climate driver in both runs. | Difference in vegetation carbon between ends of simulations (a) and (b) divided by difference in vegetation area between end of simulations (a) and (b). |

Figure 2. Early and recent vegetation cover. (a) Early 20th century vegetation cover dominant in each cell, assuming no human land use change, using results from LPJmL. The area covered by each vegetation type in each continent defines a different region for the purposes of this analysis. (b) Recent vegetation cover assuming land use change, using results from LPJmL. In (b), cells are coloured with shades corresponding to fractional cover.

We differentiated C3 (cold temperate and boreal) and C4 (tropical, warm temperate) grasslands since they have different physiological characteristics making them differently susceptible to changes in temperature, precipitation and CO₂ levels (Blair et al 2014). We used these results to calculate normalized interaction strengths, defined generally for the effect of variable X on variable Y as (Lade et al 2020) (supplementary methods):

$$\text{normalised interaction strength} = \frac{\Delta Y}{\Delta X} \frac{X^G - X^0}{Y^G - Y^0},$$

where $\Delta X$ and $\Delta Y$ are the changes in $X$ and $Y$, respectively, and the superscripts 0 and G denote the values of the variables under pre-industrial conditions and at their guardrains, respectively. This definition allows the strengths of interactions between different pairs of Earth system processes with different units to be compared. A normalized interaction strength of 1 means that if variable $X$ moves from its pre-industrial value to its guardrail, it causes variable $Y$ to change by the difference between its pre-industrial value and its guardrail. Positive/negative normalized interaction strengths mean that an increase in impacts on $X$ (such as increased climate change, water stress, or vegetation cover loss) causes an increase/decrease in impacts on $Y$. We took values for guardrails from the regional boundaries for land and water and the global boundary for climate that were identified in the latest version of the planetary boundaries framework (Steffen et al 2015b) (supplementary methods).
We also used the CRU TS dataset to estimate the current states of land and water in the Earth system (supplementary methods). We normalized these state variables so that a normalized value 0 corresponds to pre-industrial conditions, a value 1 corresponds to its guardrail, and larger than 1 corresponds to beyond its guardrail (supplementary methods).

2.2. Feedback model
To calculate the effects of interactions, we assembled the interaction strengths into an interaction matrix \( B \). The change in impact on Earth system state variables \( \Delta x \) in response to a change in pressures on the state variables \( \Delta d \) can then be calculated by (see supplementary methods):

\[
\Delta x = (I - B)^{-1} \Delta d,
\]

where \( I \) is the identity matrix and \( \Delta x \) and \( \Delta d \) are vectors of normalized state variables.

This approach to modelling feedbacks assumes linear interactions and calculates impacts at equilibrium, where we use the term ‘equilibrium’ in the dynamical systems sense of not changing over time (Izhikevich 2007). The linear assumption is consistent with the generally linear interactions independent of RCP scenario that were estimated by LPJmL (see section 3), but ignores the potential effects of tipping points in the Earth system (Lenton et al 2008, 2019). Our equilibrium assumption means our analysis cannot study short-term, transient responses to changes in water flows or vegetation area. Extensions to include nonlinear and transient dynamics would require additional data to parameterize and are beyond the scope of this work.

2.3. Amplification factor
We defined the amplification factor as the changes in variables after interactions are accounted for, divided by the changes in variables before interactions are accounted for, that is,

\[
\text{amplification factor} = \frac{\| \Delta x \|}{\| \Delta d \|}.
\]

where we define a vector norm \( |x| \) that sums the state variables so that global-scale impacts on land, water and climate are weighted equally (supplementary methods) and impacts on land and water within each region are weighted equally. This definition assesses the extent to which pressures on one component of the Earth system are amplified into impacts on other components of the Earth system. An amplification factor of 1 means no net amplification, greater than one means a net amplification of pressures, less than one means Earth system interactions partially mitigate the initial pressures, and less than zero would mean that Earth system pressures lead to a net decrease of Earth system impacts. Generally, any interactions of positive (amplifying) sign will increase the amplification factor, while any positive feedback loops will accelerate this increase. Our analysis includes possible feedback loops between climate change and vegetation cover in each region (figure 1).

2.4. Prototype Earth system impact metric
To calculate our prototype Earth system impact metric, we (a) weighted the amplification factors by the current states of the Earth system \( x^{now} \), so that the metric is sensitive to how impacted the Earth system currently is, and (b) removed the normalization by the size of the pressures \( \Delta d \), so that the metric is sensitive to the magnitude of the water extraction, deforestation or carbon emissions from the individual, company, financial investor or other actor. We defined:

\[
\text{Prototype Earth system impact metric} = |\Delta x \cdot u(x^{now})|,
\]

where the function \( u \) rounds any normalized state variables that are larger than 1, that is, beyond the guardrail, down to 1, and the dot indicates the vector dot product. Defined this way, an impact factor of 1 would mean that the climate state variable, or all land state variables, or all water state variables, have moved from their planetary boundaries to twice beyond their planetary boundaries. While we expect the metric could be used to assess impacts from the activities of actors such as businesses or cities, to illustrate the metric in this study we chose a fixed standard amount of vegetation cover change (5 km\(^2\)) and water extraction (10\(^6\) m\(^3\) yr\(^{-1}\)) that gave similar impact magnitudes.

Constructed in this way, our prototype Earth system impact metric therefore: (a) incorporates impacts of multiple components of the Earth system (climate, land, water); (b) distinguishes impacts on land and water by region and vegetation type; (c) accounts for interactions between these Earth system components; (d) accounts for the current states of these Earth system components; and (e) accounts for impacts compared to guardrails for safe levels of impact.

3. Results

3.1. Interaction strengths between climate, water and land
Our results for interaction strengths show that loss of vegetation cover (corresponding to increases in the normalised state variables for vegetation cover) usually increases climate change (positive normalised interaction strength) and decreases water stress (negative normalised interaction strength),
Figure 3. Interaction strengths. Normalised interaction strengths for the effects of (a) climate change on surface water runoff, (b) climate change on vegetation cover, (c) vegetation cover change on climate and (d) vegetation cover change on runoff, using results from LPJmL over the last century. A normalized interaction strength of 1 means that if one Earth system component moves from its pre-industrial value to its guardrail, it causes another Earth system component to change by the difference between its pre-industrial value and its guardrail. Positive and negative interaction strengths mean that an increase in impacts on one Earth system component (such as increased climate change, water stress, or vegetation cover loss) cause an increase and decrease, respectively, in impacts on another Earth system component. Dashed lines indicate the globally aggregated interaction strengths estimated by Lade et al (2020). Error bars indicate one standard error, calculated from variation over grid cells. Variation over different climate models and different emission scenarios are shown in figures S1 and S2.

respectively (figure 3). These results are as expected, since deforestation leads to loss of vegetation carbon that accelerates climate change but generally leads to less penetration of rainfall into soil and therefore on average increases runoff (Sterling et al. 2013). The strongest effect of vegetation cover change on climate was found in South American tropical forest, due to the large quantities of carbon stored in Amazon rainforest. The strongest effect of vegetation cover change on runoff was found in Asian C3 and C4 grasslands; we speculate that this is due to large parts of these grasslands having been replaced
Figure 4. Amplification factors. The extent to which (a) carbon emissions and (b) vegetation cover change are amplified by Earth system interactions into impacts across the Earth system. An amplification factor of 1 means the Earth system interactions we modelled here lead to no net amplification of environmental pressures; more than 1 means net amplification; less than 1 means Earth system interactions partially mitigate environmental pressures. We weight impacts equally between climate, land and water when aggregated at the global scale (Methods). Since in our feedback model surface runoff does not affect other Earth system components (figure 1), all amplification factors for water withdrawal are 1 and not shown here. Output from historical simulations were used to generate these results; for results using future scenarios see figures S3 and S4.

by urban areas. Interaction strengths were generally consistent across historical and different future LPJmL model runs, indicating generally linear model behaviour, though generally smaller than the globally aggregated interaction strength estimated by Lade et al (2020).

The effects of climate change on runoff and vegetation cover were more variable (figure 3). Our results show that, in the absence of direct human land use change, climate change decreases loss of potential boreal, temperate and tropical forest cover, with mixed results for potential grassland cover. The results for forests are of an opposite sign to that predicted by Lade et al (2020), who based their estimate on the possible collapse of Amazon rainforests, which did not occur in our simulations. Climate change, again in the absence of direct human land use change, in our results generally increases water stress, with mixed results in a few more regions. This variability is to be expected given the strong dependence of climate-induced rainfall changes on location and the extent of warming.

3.2. Local environmental pressures amplified by Earth system interactions across scales

Interactions between land, climate and water can lead to substantial amplification of regional environmental pressures across regional and global scales (figure 4). The largest amplification factor we measured was a more than doubling of Earth system impacts from deforestation of tropical South American forest (2.5 using historical simulation, figure 4; in range 3–4 for future RCP simulations, figure S1), due to the large amounts of carbon stored in Amazon rainforest vegetation. Other tropical and temperate forests also displayed large amplification factors, demonstrating the central role of these forests in maintaining a stable Earth system.

The amplification factor we measured for climate was less than 1 (figure 4), since in our feedback model the impacts of climate change are partially compensated for by climate-induced increase in potential forest area, especially of boreal forest. This result should be treated with caution. As discussed above, LPJmL may overestimate potential boreal
forest area in response to climate change. LPJmL’s omission of permafrost release also decreases the amplification factor.

3.3. Current Earth system states
We found that most vegetation cover state variables have exceeded their guardrails (figure 5). We found greatest loss of tropical forests in Africa and North America and boreal forest in Europe, which are regions known to have experienced severe deforestation pressure (IPBES 2019). The only vegetation areas to have expanded (indicated in figure 5 by negative values) are North American and Asian boreal forests and Australian tropical forest. LPJmL is known to potentially overestimate the rate of northern expansion of boreal forests in response to climate change (Schaphoff et al 2018a); our results related to boreal forests should therefore be treated with caution. The area of Australian tropical forests may have increased due to release of pressure from regular burning by traditional owners (Bowman et al 2010), but the increase ((100%–85%) × 9.5 = 140% increase, using equation (11) in supplementary methods) is unrealistically large.

The vegetation regions experiencing greatest disruption to surface water flow were warm climate (C4) grasslands in North America and Asia, corresponding to large agricultural water use in these areas. None of the state variables, however, have transgressed their guardrails (all water state variables <1, figure 5). The planetary boundaries framework, from which our guardrails are derived, takes a globally aggregated view of consumptive water use as its indicator of human perturbation of Earth system dynamics. It does not reflect the societal pressures that manifest at catchment scale (Gleeson et al 2020), such as water shortages and local requirements for environmental water flows, although these sub-global aspects can be factored into global analyses (Gerten et al 2013, Steffen et al 2015b). In some regions, LPJmL results show that surface water runoff has slightly increased over time, giving a normalised state variable less than zero, with a likely unrealistically large increase in runoff in European boreal forests.

3.4. A prototype metric for Earth system impacts
Combining amplification factors and current Earth system states led to our prototype Earth system impact metric (figure 6). The impacts captured by the metric displayed the following patterns.

First, Earth system impacts arising from water extraction (figure 6) displayed sensitivity to the current state of surface water flow, moderated by the rainfall over the region and the total area of the region. Water withdrawal in areas experiencing current water stress, C4 grasslands in North America and Asia, would result in large Earth system impacts. Water extraction in tropical forests would generally lead to smaller Earth system impacts, due to their high levels of rainfall.

Second, in addition to the sensitivities observed for water, impacts from vegetation cover change were also amplified through Earth system interactions. The areas in which additional vegetation cover change would lead to the highest Earth system impacts were most tropical forests worldwide, temperate forests in Oceania and Africa, and C3 grasslands in Australia and Africa. Temperate forests in Oceania and tropical forests in North America received the greatest impact factor due to their small area.

3.5. Uncertainty analysis
The above amplification factor and impact metric results were generated using interaction strengths from historical model runs. Using interaction strengths from future model runs under different climate scenarios (figure S1) gave similar results for amplification factors and impact metrics (Figures S3 and S4), with variations in impact metric between scenarios generally in the range 0%–10% from the mean. Variations in amplification factor were somewhat larger, with the largest variation for vegetation cover change in South American tropical forest. Where results differed, they generally showed slightly increasing amplification factor and impact metric with increasing carbon emissions, suggesting a weakly nonlinear response. The impact metrics for surface water runoff (figure S3) were constant across scenarios since, in our feedback model, changes in surface runoff do not affect other Earth system components. Using interactions calculated by driving LPJmL with output from different climate models (figure S2) gave similar variation in interaction strengths as the variation across scenarios (figure S1).

We therefore have confidence that our prototype impact metric is robust to changes in scenario and model in the climate dataset used to drive LPJmL. There are, however, other Earth system interactions relevant to the planetary boundaries (Lade et al 2020) that we were unable to estimate using LPJmL. For example, deforestation can increase the albedo of land surfaces, thereby partially compensating for the radiative forcing arising from the atmospheric carbon dioxide released by deforestation (Bala et al 2007). Our metric may also be sensitive to the choice of region and definition of vegetation types. We have noted above some likely incorrect results for boreal forests and Australian tropical forests. Our amplification factors and impact metrics also weight the value of maintaining land and water in each region below their guardrails equally. A systematic investigation of these structural assumptions and sources of uncertainty is beyond the scope of this work but could form future work, as described in section 4 below.
Figure 5. Recent state variables. Average normalised state variables for (a) climate change, (b) vegetation cover change by vegetation region and (c) surface water runoff change by vegetation region over the last 30 years of LPJmlL’s historical simulation (Methods). A normalised state variable of 0 would indicate reference (early 20th century with no land use change) conditions, of 1 would indicate the Earth system component is at its guardrail, and greater than 1 would indicate the component is beyond its guardrail.

4. Discussion

Our findings have implications for both the science and practice of global sustainability. With regards to global sustainability science, our results quantify the interconnectedness of land, water and climate in the Earth system at regional and global scales relative to the guardrails established by the planetary boundaries. Our amplification factor identifies regions of the planet, such as South American tropical forests, that
Figure 6. Prototype Earth system impact metric. Prototype Earth system impact metric for (a) 0.1 MtC carbon emissions, (b) 5 km² vegetation cover change by vegetation region, and (c) 10⁶ m³ yr⁻¹ blue water withdrawal. Due to our use of normalised units for state variables, all values are small (of the order of 10⁻⁶). Output from historical simulations were used to generate these results; for results using future scenarios see figures S3 and S4.
possible perverse incentives. For example, targets based on such metrics must be embedded in a framework such as the conservation mitigation hierarchy (Arlidge et al. 2018) to avoid incentives including offsetting deforestation by planting monocultures. In the mitigation hierarchy, actors are encouraged to first avoid impacts; if impacts cannot be avoided then they should be minimised; if they cannot be minimised they should be remediated through restorative action at the same site; and only as a last resort should impacts be offset by improvements elsewhere. Furthermore, the impact metric presented here is regionally aggregated and should not replace environmental impact assessments or other mechanisms to assess local-scale impacts, for example on rare or threatened species. For example, that our prototype impact metric is 0 for Australian tropical forests only communicates that removing Australian tropical forest does not currently have Earth system-scale impacts on climate, land cover or water, according to our metric.

From a scholarly perspective, future modelling work could involve: pressures on more components of the Earth system, such as more of the planetary boundaries; more detailed representations of Earth system components, such as other components of the water cycle like green water and groundwater (Gleeson et al. 2020), greenhouse gases other than carbon dioxide, or more of the many facets of biodiversity (Díaz et al. 2020); more Earth system interactions, such as teleconnections involving moisture recycling (Wäng-Erlandsson et al. 2018); or other impacts, for example through changes in variability as well as mean of surface runoff or with other ecosystem impact metrics (Pfister et al. 2009). These additions could lead to more amplifying interactions and feedback loops and consequently larger estimates of amplification factors and Earth system impacts. One could also compare our results to those generated by other dynamic global vegetation models; generate impact metric results at smaller scales such as ecoregions or watersheds; use other local empirical data to assess sub-global safe operating spaces (Dearing et al. 2014); or incorporate time scales and nonlinearities into the analysis. Nonlinear interactions may contribute to the Earth system tipping into an alternative trajectory such as ‘Hothouse Earth’ (Steffen et al. 2018). The appropriate choice of guardrails, for which we here used the 2015 version of the planetary boundaries, is also an ongoing area of research. A systematic analysis of many of these factors would require a resource-intensive Earth system model intercomparison project on Earth system interactions.

We emphasize that the Earth system impact metric presented here is a prototype and see it as a foundation from which to develop more precise and nuanced understandings of Earth system interactions and impacts. Future work could include engagement with potential users of the impact metric towards resolving trade-offs between complexity of Earth system representation and usability of the metric, such as which pressures on the Earth system to include and what spatial resolution is appropriate.

Our estimation of cross-scale Earth system interaction strengths advances global sustainability science and delivers a prototype of an environmental impact metric that is savvy to Earth system interactions. We hope our results catalyse both further scientific work on extending and improving this metric and action by investors, companies, cities, governments and other actors towards a sustainable future worldwide.

Data availability statement

The data and code that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5281/zenodo.4738009.

Contributions to paper

Developing project ideas: B C, S C, I F
Modelling: S L, I F
Writing paper: S L, S C, B C, I F

Acknowledgments

I F, S C, B C and S L were funded by Vinnova (Project 2019-03128). I F and S C were also funded by the European Research Council project Earth Resilience in the Anthropocene (743080 ERA). B C was also funded by the Erling-Persson Foundation through support to the Global Economic Dynamics and the Biosphere programme (GEDB).

ORCID iDs
Steven J Lade @ https://orcid.org/0000-0001-9719-9826
Ingo Fetzer @ https://orcid.org/0000-0001-7335-5679
Beatrice Crona @ https://orcid.org/0000-0003-1617-4067

References

Alpro 2018 Sustainability update 2018 (available at: https://downloads.cfassets.net/64igdkkldi/44KZqMuuXaWPthHNaYXSrJ/6esed8ae119b8acca68c9c900011a3a/Alpro_Sustainability_update_2018.pdf)
Arlidge W N S et al 2018 A global mitigation hierarchy for nature conservation Bioscience 68 336–47
Arora V K, Boer G J, Friedlingstein P, Eby M, Jones C D, Christian J R, Bonan G, Bopp L, Brovkin V and Cadule P 2013 Carbon–concentration and carbon–climate feedbacks in CMIP5 Earth system models J. Clim. 26 5289–314
Bala G, Caldeira K, Wickett M, Phillips T J, Lobell D B, Delire C and Mirin A 2007 Combined climate and carbon-cycle effects of large-scale deforestation Proc. Natl Acad. Sci. USA 104 6550–5
Blair J, Nippert J and Briggs J 2014 Grassland ecology Ecology and the Environment ed Monson R The Plant Sciences (New York: Springer) 8 389–423 (available at: https://link.springer.com/referenceworkentry/10.1007/978-1-4614-7501-9_14)
Bowman D M J S, Murphy B P and Banfai D S 2010 Has global environmental change caused monsoon rainforests to expand in the Australian monsoon tropics? Landsc. Ecol. 25 1247–60

Cranston G and Steffen W 2019 Linking planetary boundaries to business: part of Kering’s series on planetary boundaries for business (Cambridge: Kering) (available at: www.cisl.cam.ac.uk/resources/publication-pdfs/linking-planetary-boundaries.pdf (Accessed 11 October 2021))

Crona B, Folke C and Galaz V 2021 The anthropocene reality of financial risk One Earth 4 618–28

Dearing J A et al 2014 Safe and just operating spaces for regional social-ecological systems Glob. Environ. Change 28 227–38

Díaz S et al 2020 Set ambitious goals for biodiversity and sustainability Science 370 411–15

Friedlingstein P et al 2006 Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison J. Clim. 19 3337–53

Gerten D, Hoff H, Rockström J, Jägermeyr J, Kummel M and Pastor A V 2013 Towards a revised planetary boundary for consumptive freshwater use: role of environmental flow requirements Carr. Opin. Environ. Sustain. 5 551–8

Gleeson T et al 2020 The water planetary boundary: interrogation and revision One Earth 2 223–34

Harris I, Jones P D, Osborn T J and Lister D H 2014 Updated high-resolution grids of monthly climatic observations—the CRU TS3.10 dataset Int. J. Climatol. 34 623–42

IPBES 2019 Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services ed E S Brondízio, J Settele, S Díaz and H T Ngo (Bonn: IPBES secretariat)

Izhikevich E M 2007 Equilibrium Scholarpedia 2 2014

Keys P W, Galaz V, Dyer M, Matthews N, Folke C, Nyström M and Cornell S E 2019 Anthropocene risk Nat. Sustain. 2 667–73

Lade S J et al 2018 Analytically tractable climate–carbon cycle feedbacks under 21st century anthropogenic forcing Earth Syst. Dyn. 9 507–23

Lade S J, Steffen W, de Vries W, Carpenter S R, Donges J F, Gerten D, Hoff H, Newbold T, Richardson K and Rockström J 2020 Human impacts on planetary boundaries amplified by Earth system interactions Nat. Sustain. 3 119–28

Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth’s climate system Proc. Natl Acad. Sci. 105 1786–93

Lenton T M, Rockström J, Gaffney O, Rahmstorf S, Richardson K, Steffen W and Schellnhuber H J 2019 Climate tipping points—too risky to bet against Nature 575 592–5

Liu J et al 2013 Framing sustainability in a telecoupled world Ecol. Soc. 18 36

Patricio J, Elliott M, Mazik K, Papadopoulos K-N and Smith C J 2016 DPSIR—two decades of trying to develop a unifying framework for marine environmental management? Front. Mar. Sci. 3 177

Pfister S, Koehler A and Hellweg S 2009 Assessing the environmental impacts of freshwater consumption in LCA Environ. Sci. Technol. 43 4098–104

Perus V 2020 A single apex target for biodiversity would be bad news for both nature and people Nat. Ecol. Evol. 4 768–9

SASB 2015 Agricultural Products: Sustainability Accounting Standard (San Francisco, CA: Sustainability Accounting Standards Board) (available at: www.sasb.org/wp-content/uploads/2015/07/CN0101_Agricultural-Products_Standard.pdf) (Accessed 11 October 2021)

Schaffopol S et al 2018a LPJmL4—a dynamic global vegetation model with managed land—part 1: model description Geosci. Model Dev. 11 1343–75

Schaffopol S et al 2018b LPJmL4—a dynamic global vegetation model with managed land—part 2: model evaluation Geosci. Model Dev. 11 1377–403

Steffen W et al 2018 Trajectories of the earth system in the anthropocene Proc. Natl Acad. Sci. USA 115 8252–9

Steffen W, Broadgate W, Deutsch L, Gaffney O and Ludwig C 2015a The trajectory of the anthropocene: the great acceleration Anthr. Rev. 2 81–98

Steffen W, Richardson K, Rockström J, Cornell S E, Fetter I, Bennett E M, Biggs R, Carpenter S R, de Vries W and de Wit C A 2015b Planetary boundaries: guiding human development on a changing planet Science 347 1259855

Sterlin S M, Ducharme A and Polcher J 2013 The impact of global land-cover change on the terrestrial water cycle Nat. Clim. Change 3 385–90

Trenberth K E, Dai A, van der Schrier G, Jones P D, Barichivich J, Griffa K R and Sheffield J 2014 Global warming and changes in drought Nat. Clim. Change 4 17–22

Wang-Erlandsson L, Fetter I, Keys P W, van der Ent R J, Savenije H H G and Gordon L J 2018 Remote land use impacts on river flows through atmospheric teleconnections Hydrol. Earth Syst. Sci. 22 4311–28

Wasszowski L, Frieler K, Huber V, Piontek F, Serdeczny O and Schewe J 2014 The inter-sectoral impact model intercomparison project (ISI-MIP): project framework Proc. Natl Acad. Sci. USA 111 3228–32

World Economic Forum 2019 The Global Risks Report 2019 (available at: www.weforum.org/reports/the-global-risks-report-2019) (Accessed 11 October 2021)

Yohe G and Tol R 2000 Adaptation and the guardrail approach to tolerable climate change Societal Adaptations to Climate Variability and Change ed S M Kane and G W Yohe (Dordrecht: Springer) pp 103–28