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Cautionary Remarks on the Planetary Boundary Visualisation

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Abstract. The Planetary Boundary (PB) concept has captured attention across academia and the public alike. Its unique visual representation has been key to the development of the concept and its dissemination. In this commentary, we outline three areas of concern to facilitate further enhancement in the PB concept's visualisation. Firstly, the radial bar plot leads to a quadratic scaling of the effect sizes. Secondly, the colour gradations denoting the risk of each boundary transgression use complex non-linear patterns, which complicates interpretation. Thirdly, the conjunction of quadratic effect scaling and specific colour coding may unintentionally amplify the perception of high-risk areas. We recommend a careful revision of the visual language employed in PB communication, aiming to address these concerns.

1 Introduction

Our planet faces multifaceted pressures, as corroborated by comprehensive reports like those from the IPCC on climate change and the IPBES on biodiversity change (IPBES, 2019; IPCC, 2023), encapsulating numerous additional human-induced Earth system changes. The Planetary Boundary (PB) concept (Rockström et al., 2009a, b) was designed as a framework to provides a unified perspective on altering various Earth system dimensions. It identifies thresholds, termed 'Planetary Boundaries', within which humans and other organisms can coexist sustainably, thus ensuring the preservation of Earth's vital life-support systems. With its clarity, the PB concept has emerged as a widely recognized tool for communicating the global change challenges of our era to decision-makers (Steffen et al., 2015). Given its broad scope, it is not surprising that the PB concept has sparked debate and controversy (Montoya et al., 2018; Rockström et al., 2018; Biermann and Kim, 2020). In response, the PB concept has seen refinements. More recent interpretations address initial omissions of interactions among boundaries (addressed in Steffen et al., 2015) and the absence of spatial mapping (introduced in Richardson et al., 2023). The remaining critiques are summarized by Tandon (2023). However, our aim here is not to critique the PB concept; for that, we redirect readers to the pertinent literature. Instead, we shift our focus to another facet that has thus far remained unaddressed in the discussion.

Since its inception, the Planetary Boundary (PB) concept has consistently featured a powerful visualization. Geere (2020) recounts an intriguing backstory. The conceptual seed for the PB concept, as described by him, was sown by Bo Ekman, founder of the Tällberg Foundation. Ekman envisioned the Earth as a crucial stakeholder at every negotiation table. This figurative idea was then scientifically articulated by Johan Röckström and underpinned by the first PB figure in Rockström et al. (2009b).

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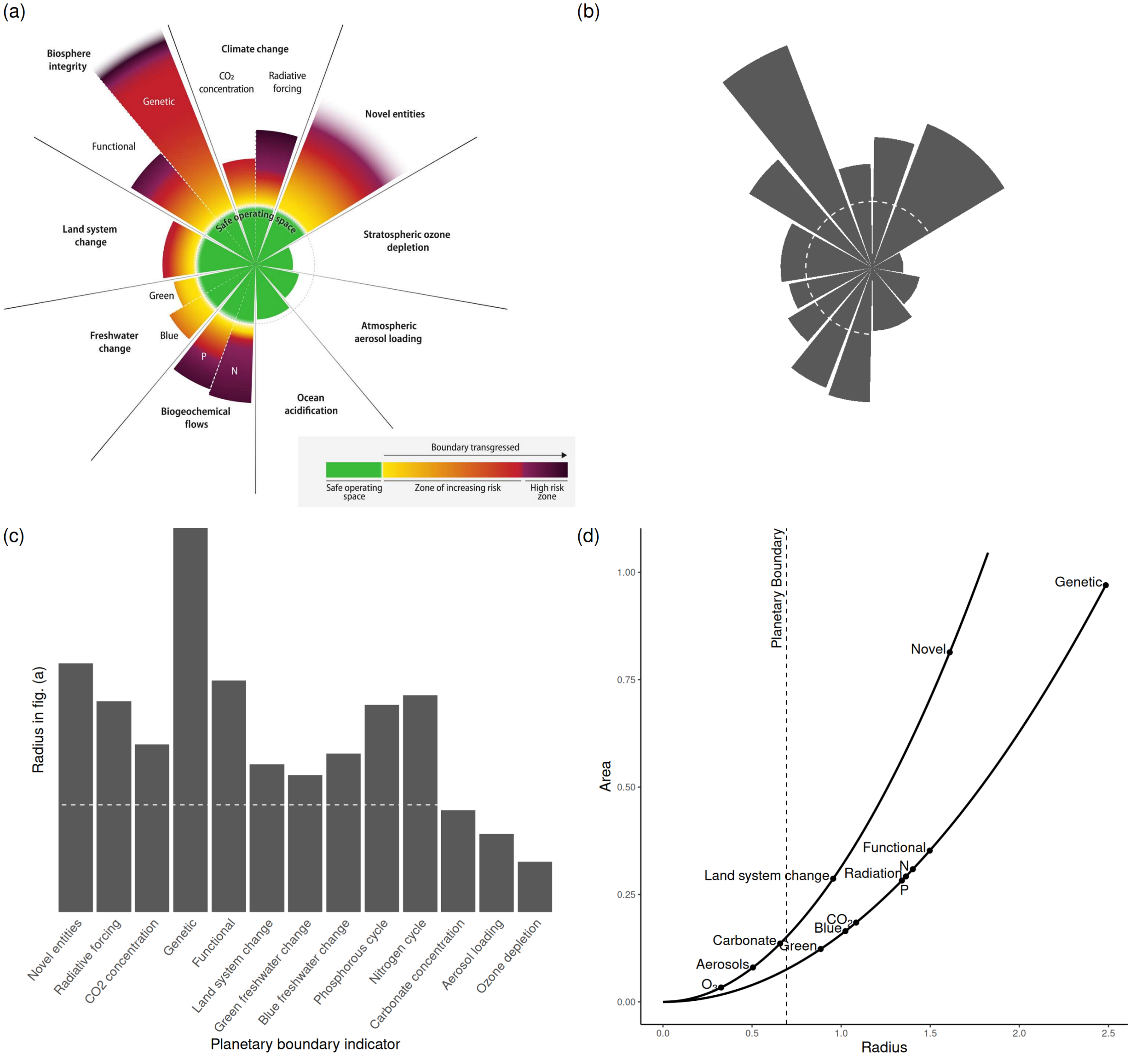

Figure 1. Scaling issues inherent in the PB concept visualisation. (a) The latest representation of the planetary boundary concept as a radial bar plot, where indicators representing different boundaries are shown as wedges. The radius of the wedge represents the value of the indicator. Source: Richardson et al. (2023), extracted from the article pdf file, figure released under the Creative Commons Attribution NonCommercial License 4.0 CC BY-NC, https://creativecommons.org/licenses/by-nc/4.0/. (b) The area representation of the PBs as depicted in the original figure in (a). A small difference in the scaling is explained in the text. (c) Actual effect sizes as reported in Richardson et al. (2023). (d) Comparison of the reported PB values to the area shown. The scaling exhibits two distinct curves, as some PBs are divided into two segments. This leads to a halving of the value of the angle θ and respective area.

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However, it was likely the version in Rockström et al. (2009a), heavily revised by Wesley Fernandes, an art director with Nature, that made a striking impact, as noted by Geere (2020). This figure employs a radial bar plot, with each wedge representing a different PB and the safe operating space marked by a constant radius. Morseletto (2017) conducted an in-depth analysis of this figure and concluded that it serves as a prime example of science communication, being understandable, meaningful, and engaging. This perception appears to be widely shared, as the figure has been reproduced and adapted extensively (e.g. Nash et al., 2017; Persson et al., 2022; Bachmann et al., 2023, and others), and the concept has even been transferred to other branches of science, such as describing the dimensions of forest disturbance attributes (Turner and Seidl, 2023).

The most recent iteration by Richardson et al. (2023, as reproduced in fig. 1a) introduces a substantial extension. It adds color gradients intended to illustrate how the transgression of PBs translates into escalating risks. Also this figure has been showcased and replicated by numerous global news outlets, achieving vast reach. At first glance, the figure seems to provide an intuitive visualization of the core messages of the Planetary Boundary (PB) concept as interpreted by Morseletto (2017). However, we contend that the current graphical representation of the PB concept and its derivatives, though visually compelling, may inadvertently mislead its audience. Here, we scrutinise the visualisation techniques employed in the PB concept and discuss potential pitfalls and enhancements. Our aim is to initiate a discussion towards developing a visualisation strategy in which the visual language accurately conveys the underlying scientific concepts.

2 Scaling of effect size

The figure in question (fig. 1a) presents a radial alignment. In fig. 1b, we recreate the latest figure presented in Richardson et al. (2023), by omitting the risk indicators that are depicted as colours. This variant focuses on the effect sizes, a uni-dimensional value—the distance to the centre. Tabular data of this kind would typically be represented as a bar chart, as illustrated in fig. 1c. However, due to the radial configuration, the displayed area scales quadratically with the intended value of the variable:

$$A_r = 0.5r^2\theta \propto r^2 \tag{1}$$

where A_r is the area of the wedge, r is the radius (i.e., the value of the PB indicator variable), and θ is the angle of the wedge, as shown in fig. 1c. The area of the wedge is perceived as visual weight, which can cause the visual impression conveyed by this plot to not accurately reflect the underlying data, a distortion effect well-documented in the scientific visualisation literature. In his seminal work, 'The Visual Display of Quantitative Information', Tufte (2001) addresses the problem of visualisations where the size of the effect scales differently in the visualisation compared to the data, advocating for representations where the size of the effect shown in graphics is proportional to the size of the effect in the data.

That the scaling is a particular issue for radial bar plots, known by various names such as 'radial bar chart', 'radar graph', 'nightingale glyph', 'rose diagram', and 'polar-area diagram', has been apparent since their inception by Florence Nightingale (Nightingale, 1858). Distinguished as a pioneer in statistical graphics (among other disciplines), Nightingale depicted deaths in British military hospitals during the Crimean War (1854-56; Cohen, 1984; Brasseur, 2005). Aware of the inherent scaling challenges, she opted for the wedge area rather than the radius to represent the effect sizes of the data (Cohen, 1984), a choice

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that could indicate the way for an alternative approach to visualizing the PB concept. However, the efficacy of radial charts is debatable. Waldner et al. (2019), for instance, shows that radial charts may be less intuitive for human interpretation compared to Cartesian coordinate systems, even for naturally cyclic patterns such as diurnal or seasonal events.

3 Scaling of colour map

The PB figure (fig. 1a) is colour-coded to show the risk associated with a transgressed PB. This method is reminiscent of the different assessment reports by the IPCC, where so-called 'burning embers' visualise the risks from climate change for various aspects/sectors under different global warming scenarios. These 'burning embers' have also generated considerable attention (for a review on their development, see Zommers et al., 2020) by indicating that certain levels of global warming lead to high-risk zones in specific sectors or impact domains. However, the representation of risks by the PB figure is notably more complex, which prompts the question: why is this the case?

The colour map employed is derived from Inferno (van der Walt and Smith, 2020). Inferno is a colour-map that has been widely adopted and is considered an excellent choice for a continuous colour scale due to its visual uniformity (see fig. 2a), meaning the perceived difference between colours is proportional to the difference in the values they represent (Crameri et al., 2020). In fig.2, we have extracted the colour gradients of the risks associated with the transgression of the PBs and displayed them against the value of the PB itself. To quantify this relationship, we have applied the following formula:

$$r = \log_e\left(\frac{x - \overline{x}_{\text{holocene}}}{x_{\text{PB}} - \overline{x}_{\text{holocene}}} + 1\right), \tag{2}$$

to reconstruct r, the radius of the corresponding wedge in the PB visualisation by Richardson et al. (2023) as a scaling factor, where x is the PB indicator variable, $\overline{x}_{\text{holocene}}$ is the Holocene mean of the PB indicator variable, and x_{PB} is the threshold defined as planetary boundary. This normalization places the planetary boundary at $\log_e(2)$ and the holocene mean at 0[1]. Values have been taken from table 1 in Richardson et al. (2023)[2]. The y-axis in fig. 2 is the cumulative distance along the colour gradient in CIELAB2000 colour space (Sharma et al., 2005; Sánchez Beeckman, 2021).

Fig. 2 shows that the risk scales for each PB in a very different manner, and the nonlinearity of the scaling is not comparable. For instance, the PB 'Biosphere integrity/Genetic' is the most overshot boundary and the one where the high risk zone is furthest away but the yellow–red gradient still shows mostly red and very little yellow (compare fig. 1a and fig. 2d). In case of the PB 'Biogeochemcial flows/N' the gradient is the one furthest in the purple high risk zone, but the yellow–red gradient is mostly yellow (compare fig. 1a and fig. 2j). Moreover, the transition from red to purple on the colour scale is much more abrupt than anywhere else in the circular bar plot. Such variations in scaling are not clarified by Richardson et al. (2023). While we

[1] As the viewer can see in fig. 1a and b, the ratio between the end of the wedges, the centre and the planetary boundary does not quite match the one in fig. 1a. We also set the current value of the 'Genetics' wedge to 110 E/MSY (extinctions per million species-years), Richardson et al. (2023) give > 100 E/MSY as a value but their figure seems to depict a value very close to 100 E/MSY, which makes this bar appear a little bit larger in fig. 1b

[2] We noted that there seems to be a numerical error in the original visualisation: The pre-industrial Holocene values for blue and green water appropriation have to be either 0% (they are 9.4% and 9.8% respectively) or their wedges in the figure have to be much longer.

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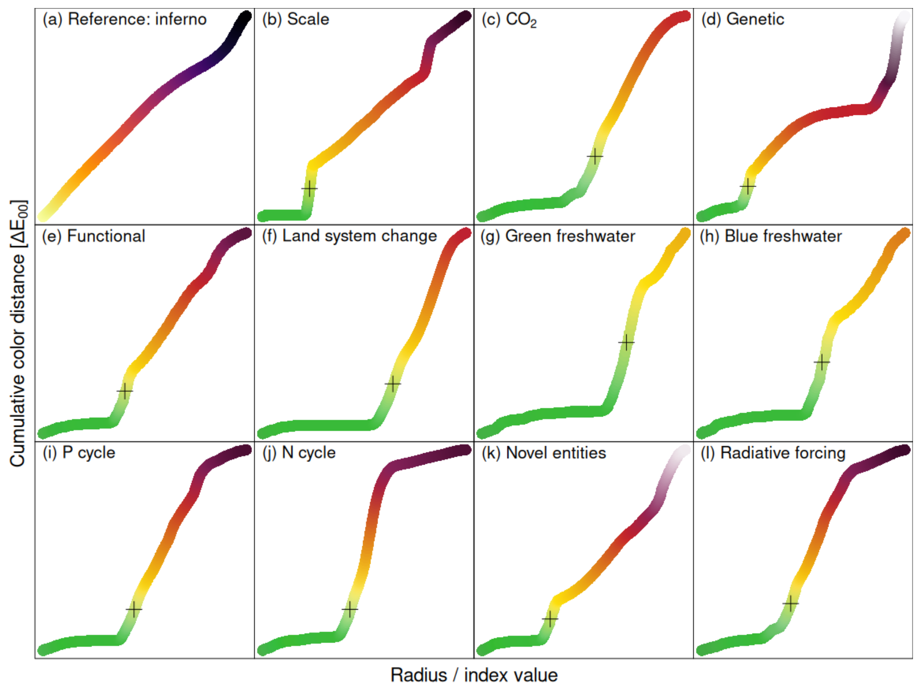

Figure 2. The plots show the distance of the indicator along the transgression of the PB vs. the risk as shown as distance in perceptual colourspace (CIEDE2000, Sharma et al. 2005, Sánchez Beeckman 2021). (a) colour map "Inferno" as reference for a linear colour space, (b) We show the "Scale" of the colour map shown on the bottom of fig. 1a. In subplots (c) to (l) we show how the cumulative colour distance grows as a function of the change in the PB. Data has been extracted from fig. 1a.

assume that the authors have quantified these transitions, we suggest that this form of visualising them is too subtle and does not allow the viewer to properly quantify the risk progression from the plot.

In the 'burning embers' diagrams, the bars are arranged according to the intensity of the associated risk, which provides a clear gradient of risk, thus facilitating more straightforward visual interpretation. Conversely, the PB visualisation, informative as it is, lacks this arrangement and uses a highly nonlinear and less transparent scaling of risk, potentially complicating the visual interpretation.

From this discussion, two logical alternatives for visualising the PB concept emerge and are presented in fig. 3. Option one is choosing a Cartesian coordinate system (fig. 3a) to circumvent issues of quadratic scaling. However, for those preferring the radial bar plot, the practice of scaling the wedge area as Nightingale demonstrated should be considered (fig. 3b) to rectify the scaling distortion. Additionally, substituting the continuous and somewhat complex colour scale for a discrete one yields an unambiguous visual representation. As stop light colour coding might be misconceived (Geere, 2020), we choose here two red colours that show the transgression region and a neutral colour for the within-boundary level. In both alternatives, we have arranged the bars in a rough order of decreasing transgression while maintaining group cohesion. Our sketch does not depict the variable grouping. While these visualisations may not possess the artistic elegance of the original, they should convey the

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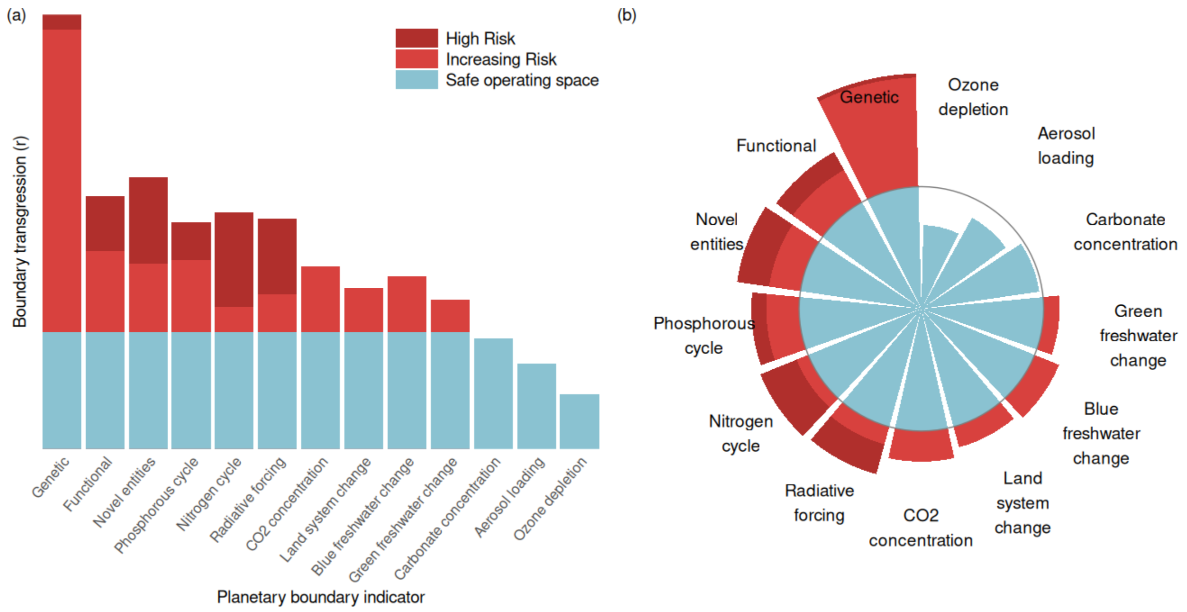

Figure 3. Two approaches to alleviate the PB visualisation issues: (a) Translating the PB figure into Cartesian coordinates and choosing a discreet colours bar - visually unattractive, but precise. The bars have been reorganized approximately by size. (b) Maintaining the circular bar chart, but scaling the wedge area by the effect sizes of the underlying variable. colours are discrete risk levels.

underlying data more precisely. Of course, fig. 3 also has limitations, such as the simplified portrayal of increasing risk and the omission of uncertainty visualisation; however, these are outside the scope of this commentary. Our intent is to spark a dialogue on the visual representation of the PB concept.

4 Conclusions

In analysing the radial visualisation of the Planetary Boundary concept, we note two areas of concern. Firstly, the quadratic, area-based scaling effect may amplify the perceived transgression of PBs. Secondly, the highly nonlinear risk mapping functions used could potentially complicate the interpretation. Considering the interplay between area and colour perception (Solso, 1994), a third issue emerges: The dark, high-risk colours might compound the quadratic effect - an effect that is, however, very hard to quantify. Given the PB concept's aim to assist decision-makers (Steffen et al., 2015), we advocate for the development of a more precise visual language. The 'burning ember' approach (Zommers et al., 2020) presents one possible alternative. Nevertheless, exploring other representations, such as two-dimensional plots or an ordinal discretization of the colour scale, merits further consideration.

Code availability. Figures can be reproduced from https://github.com/mafla/PlanetaryBoundaryVisuals

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References

Bachmann, M., Zibunas, C., Hartmann, J., Tulus, V., Suh, S., Guillén-Gosálbez, G., and Bardow, A.: Towards circular plastics within planetary boundaries, Nature Sustainability, 6, 599–610, 2023.

Biermann, F. and Kim, R. E.: The boundaries of the planetary boundary framework: a critical appraisal of approaches to define a "safe operating space" for humanity, Annual Review of Environment and Resources, 45, 497–521, 2020.

Brasseur, L.: Florence Nightingale's Visual Rhetoric in the Rose Diagrams, Technical Communication Quarterly, 14, 161–182, https://doi.org/10.1207/s15427625tcq1402_3, 2005.

Cohen, I. B.: Florence Nightingale, Scientific American, 250, 128–137, 1984.

Crameri, F., Shephard, G. E., and Heron, P. J.: The misuse of colour in science communication, Nature communications, 11, 5444, 2020.

Geere, D.: A Dashboard for Planet Earth, Nightingale: The Journal of Data Visualization Society, https://medium.com/nightingale/a-dashboard-for-planet-earth-9abafdbd2749, accessed: 2023-11-15, 2020.

IPBES: Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Tech. rep., IPBES secretariat, Bonn, Germany, https://doi.org/10.5281/zenodo.3831673, version Number: 1, 2019.

IPCC: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, https://doi.org/10.59327/IPCC/AR6-9789291691647, 2023.

Montoya, J. M., Donohue, I., and Pimm, S. L.: Planetary boundaries for biodiversity: implausible science, pernicious policies, Trends in ecology & evolution, 33, 71–73, 2018.

Morseletto, P.: Analysing the influence of visualisations in global environmental governance, Environmental Science & Policy, 78, 40–48, 2017.

Nash, K. L., Cvitanovic, C., Fulton, E. A., Halpern, B. S., Milner-Gulland, E., Watson, R. A., and Blanchard, J. L.: Planetary boundaries for a blue planet, Nature ecology & evolution, 1, 1625–1634, 2017.

Nightingale, F.: Notes on Matters Affecting the Health, Efficiency and Hospital Administration of the British Army, Royal Collection Trust, https://www.rct.uk/collection/1075240/notes-on-matters-affecting-the-health-efficiency-and-hospital-administration-of, 1858.

Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., De Wit, C. A., Diamond, M. L., Fantke, P., Hassello¨v, M., MacLeod, M., Ryberg, M. W., et al.: Outside the safe operating space of the planetary boundary for novel entities, Environmental science & technology, 56, 1510–1521, 2022.

Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., Cornell, S. E., Donges, J. F., Drüke, M., Fetzer, I., Bala, G., von Bloh, W., et al.: Earth beyond six of nine planetary boundaries, Science Advances, 9, eadh2458, 2023.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., et al.: A safe operating space for humanity, Nature, 461, 472–475, 2009a.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H. J., et al.: Planetary boundaries: exploring the safe operating space for humanity, Ecology and Society, 14, 2009b.

Rockström, J., Richardson, K., Steffen, W., and Mace, G.: Planetary boundaries: Separating fact from fiction. A response to Montoya et al., Trends in ecology & evolution, 33, 233–234, 2018.

Sharma, G., Wu, W., and Dalal, E. N.: The CIEDE2000 Color-Difference Formula: Implementation Notes, Supplementary Test Data, and Mathematical Observations, Color Research & Application, 30, 21–30, https://doi.org/10.1002/col.20070, 2005.

https://doi.org/10.5194/egusphere-2023-2760
Preprint. Discussion started: 11 December 2023

Solso, R. L.: Cognition and the visual arts, MIT press, 1994.

Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R., Carpenter, S. R., De Vries, W., De Wit, C. A., et al.: Planetary boundaries: Guiding human development on a changing planet, Science, 347, 1259 855, 2015.

Sánchez Beeckman, M.: ColorNameR: Give Colors a Name, https://CRAN.R-project.org/package=ColorNameR, r package version 0.1.0, 2021.

Tandon, A.: 'Safe and just' climate boundary has already been breached, says contested study, Online, https://www.carbonbrief.org/safe-and-just-climate-boundary-has-already-been-breached-says-contested-study/, accessed: Sept. 28, 2023, 2023.

Tufte, E. R.: The visual display of quantitative information, vol. 2, Graphics press Cheshire, CT, 2001.

Turner, M. G. and Seidl, R.: Novel disturbance regimes and ecological responses, Annual Review of Ecology, Evolution, and Systematics, 54, 63–83, 2023.

van der Walt, S. and Smith, N.: MPL Colour Maps, https://bids.github.io/colormap, last accessed on 2023-10-10, 2020.

Waldner, M., Diehl, A., Gracanin, D., Splechtna, R., Delrieux, C., and Matkovic, K.: A Comparison of Radial and Linear Charts for Visualizing Daily Patterns, IEEE Transactions on Visualization and Computer Graphics, pp. 1–1, https://doi.org/10.1109/TVCG.2019.2934784, 2019.

Zommers, Z., Marbaix, P., Fischlin, A., Ibrahim, Z. Z., Grant, S., Magnan, A. K., Pörtner, H.-O., Howden, M., Calvin, K., Warner, K., et al.: Burning embers: towards more transparent and robust climate-change risk assessments, Nature Reviews Earth & Environment, 1, 516–529, 2020.