

Growth and diffusion of the planetary boundaries concept

OLA JOHANSSON



Johansson, O. (2025) Growth and diffusion of the planetary boundaries concept. *Fennia* 203(2) 253–272 <https://doi.org/10.11143/fennia.146848>

The planetary boundaries are an Earth science concept that aims to comprehensively assess human-caused disturbances on the planet. First developed in 2009, the basic premise is that there are thresholds for a series of Earth systems that, if crossed, will cause abrupt and potentially catastrophic environmental change. As such, planetary boundaries are useful to frame sustainability objectives and practices. This article investigates the scholarly diffusion of planetary boundaries. How did it take off and spread? Using academic databases, primarily in English, I trace the growth of the concept over time, by the geographic location of scholars, as well as their disciplinary affiliations. Using citation counts, the most influential papers that have diffused the concept are identified. The results indicate that the planetary boundaries have penetrated a wide variety of different academic disciplines, although such research is predominantly European, a pattern that can be explained both nearness/farness spatiality and classic diffusion theory. Moreover, the temporal expansion of planetary boundaries is compared to other, well-established sustainability concepts. Fewer studies currently address planetary boundaries compared to the related concepts Anthropocene and ecological footprint; however, the growth rate of planetary boundaries research is comparable to trends when those concepts were new. Based on how articles engage with the planetary boundaries concept (categorized as Level A–C), I conclude that most researchers use the concept as a background idea to frame their research questions. Although quantitatively fewer, some studies continuously assess and refine the planetary boundary concept itself. The planetary boundaries have diffused sufficiently so that multiple academic fields have adopted it as a foundational research principle.

Keywords: planetary boundaries; diffusion; history of science; environmental crises; sustainability concepts

Ola Johansson (<https://orcid.org/0000-0003-3183-5265>), Department of Geosciences and the Environment, University of Pittsburgh at Johnstown, USA.
E-Mail: johans@pitt.edu

Introduction

In 2022, I temporarily resided in Amsterdam, the Netherlands to explore urban sustainability. One public-private initiative framed the city's socio-economic and environmental progress around ideas such as living in balance with existing resources, circular economies, reducing the ecological footprint, and pursuing regenerative development (Doughnut Economics Action Lab 2020). In particular, the report utilized the planetary boundaries concept as a foundation for its vision of sustainable planning. The use of an Earth systems science concept in urban policy raises some intriguing questions. It suggests that local stakeholders have 'found' a global science concept and engaged in a scalar transformation that makes it potentially useful locally. Moreover, the concept has moved from scientific inquiry to the realm of advancing human well-being. How did that happen? Where did it come from?

This paper is not about Amsterdam, nor about urban policy. Rather, I want to review the global growth and diffusion of planetary boundaries as a scientific concept. To what extent has it taken off and spread among (English-language) scholarly communities, from the environmental sciences to the social sciences, and other academic and non-academic fields? The Amsterdam example also suggests that planetary boundaries may be well-known in western Europe, but is it adopted elsewhere in the world? Biermann and Kim (2020, 497) write that the "planetary boundaries framework has been influential in generating academic debate and in shaping research projects and policy recommendations worldwide", yet the details of that diffusion process have yet to be penciled in. As the planetary boundaries have "helped redefine the scientific discourse over the past decade...and clearly advanced older debates on planetary limits" (Kim & Kotzé 2021, 3), it is important to study the scientific process by which this spread has been taking place and how that compares to other similar scientific concepts. The way environmental crises are understood depends on how they are framed in both science and society. Therefore, a study on the diffusion of planetary boundaries is also socially relevant as its integration into governance solutions to environmental problems, as well as legal frameworks, may be dependent on how scientific discourses spread locally, regionally, and globally. A significant caveat is that this study can only illuminate how the concept is used in research published in English, not how it is discussed in other linguistic contexts.

Planetary boundaries and other sustainability concepts

Originating in Earth systems sciences, the planetary boundaries concept is relatively new. Aiming to comprehensively assesses human-caused disturbances on the planet, it was originally proposed in the 2009 article 'Planetary Boundaries: Exploring the Safe Operating Space for Humanity' in *Ecology and Society*, authored by environmental scientist Rockström and 28 of his colleagues, many of whom were affiliated with the Stockholm Resilience Centre, a research center at Stockholm University, Sweden. The basic premise is that there are thresholds for a series of Earth systems that, if crossed, are expected to cause abrupt and potentially catastrophic environmental change. There are nine such systems and processes: freshwater, stratospheric ozone, atmospheric aerosols (particulate matter), ocean acidification, biochemical flows (anthropogenic nitrogen and phosphorus), novel entities (chemical pollution), land-systems change (deforestation), biospheric integrity (biodiversity), and climate change. Societies must live within the boundaries of these systems, what the authors refer to as humanity's 'safe operating space,' if we are to preserve a stable, livable environment. The planetary boundaries are typically visualized in a circular chart (Figure 1) with safe operating space depicted in the middle and the nine systems extending outward to different degrees, depending on to what extent they have or have not transgressed planetary boundaries. Conclusions from recent research are not optimistic; most of the boundaries may already have been transgressed (Richardson *et al.* 2023).

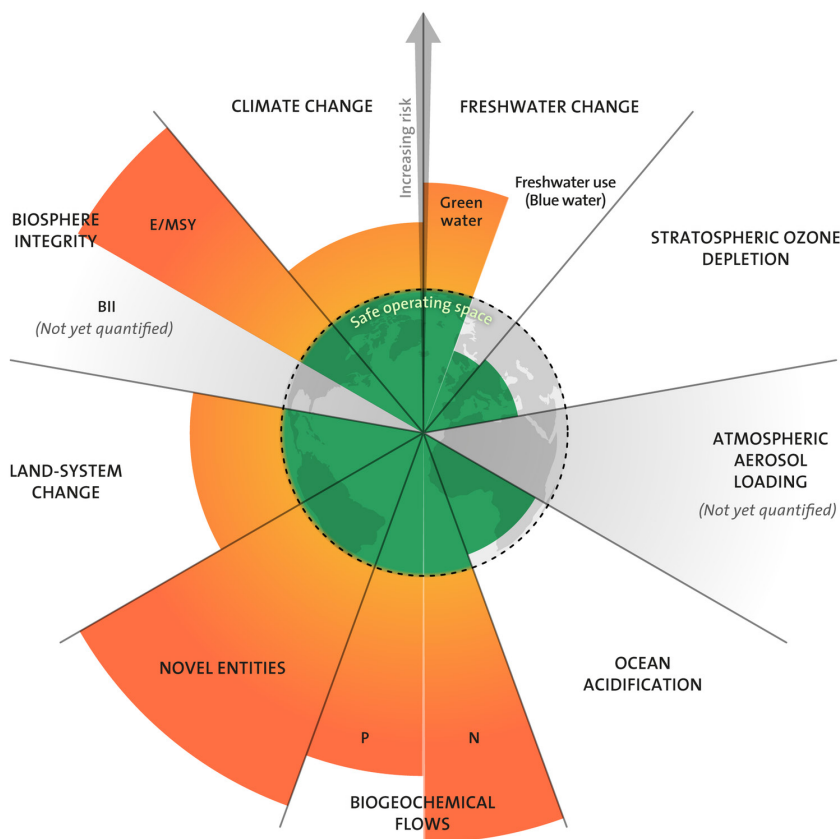


Fig. 1. Visualization of planetary boundaries showing recent estimates on levels of transgression. Designed by Azote for Stockholm Resilience Centre. Source: Wang-Erlandsson and colleagues 2022. Used under license from creativecommons.org.

The planetary boundaries framework has been critiqued from various scientific and socio-economic perspectives. Biermann and Kim (2020) offer a broad assessment of critiques while Kim and Kotzé (2021) focus on social science viewpoints. Key concerns include the uncertainty of threshold levels; who determines what constitute safe operating space and whether that is a purely scientific endeavor or if it should include policy-makers and other stakeholders; whether nine boundaries are the most appropriate conceptualization; the limited concern for social justice and global inequality and the potential role for planetary boundaries to be used as a way to limit development in the Global South; the complex interdependency among boundaries both from a scientific and socio-political perspective, and so on. Over time, some of the shortcomings have been addressed by the progenitors of the concept and by a growing body of independent scholarly work. For example, one important socio-economic extension of planetary boundaries is the doughnut idea proposed by Raworth (2017). The doughnut refers to the visualization in Figure 1 where the safe operating space is reconceptualized as a social space in which humanity thrives, as measured by United Nations's (UN) Sustainable Development Goals. It is not the objective of this article to further assess the veracity of the concept; suffice to say that the popularity of planetary boundaries suggests that it is perceived as a robust and important concept, although not without shortcomings. For his work, Rockström was awarded the prestigious Tyler Prize for Environmental Achievement, informally referred to as the 'environmental Nobel Prize,' in 2024.

Emphasizing human-caused environmental change, planetary boundaries build on earlier formulations about sustainability. Such concepts integrate interrelated ideas and are complementary in the understanding of environmental crises that affect Earth. However, they are also in competition with each other, for public and academic attention, and how to most effectively communicate challenging environmental problems. One important antecedent to planetary boundaries is the limits to growth perspective. It originated with a 1972 report issued by the Club of Rome (Meadows *et al.* 1972), an environmental advocacy group consisting of economic, political, and scientific elites. The report garnered significant attention through the early use of computer models which connected population growth, material consumption, and agriculture with projected resource depletion and pollution. If business-as-usual prevailed, the report warned that a societal collapse was inevitable within 100 years, resulting in a sudden decline in population and economic output. On the one hand, limits to growth is aligned with planetary boundaries as it is concerned with limits that, if transgressed, will have profound consequences. Both frameworks place a great degree of significance on environmental thresholds. A difference, though, is that limits to growth is more explicitly anthropocentric in its perspective, as it is structured around a series of human-societal variables. Its model-driven method is also distinct from the environmental data observations that underpin planetary boundaries. Fifty years later, the limits to growth perspective continues to have proponents. Updates have arrived at conclusions similar to the original report (Meadows *et al.* 2004) and the centrality of climate change as a driver of environmental crisis has ensured the continued relevance of limits to growth (Kahn 2022). The Club of Rome (2020) has also integrated planetary boundaries in its recent environmental advocacy. A logical implication of limits to growth is that current economic expansion is unsustainable. Therefore, some argue that economic models that underpin the capitalist system, as now practiced, must be rejected. Instead, an ecologically centered economy calls for a radically different approach, such as 'degrowth' (Kallis *et al.* 2018). The emerging degrowth perspective suggests that a reduction of resource and energy use is imperative to stay within the planetary boundaries.

Another related and prominent concept is the ecological footprint (and its derivatives with narrower emphasis, such as carbon footprint and water footprint), which dates from the early 1990s (Rees 1992). The concept can be described as an accounting measure where the Earth provides ecological assets that humans need to sustain their consumption, such as land for food production and living space, oceans for fish protein, and forest for timber products as well as a capacity to absorb waste, in particular greenhouse gas emissions. If the Earth (or sometimes calculated on a regional, country, or individual level) does not have enough biocapacity for society's consumption needs, our ecological footprint exceeds biologically productive land, and we run a deficit. This overshoot, as most ecological footprint calculations indicate, is conceptually related to exceeding planetary boundaries. The footprint's ecological assets are also reminiscent of the nine planetary boundaries.

Planetary boundaries can also be effectively integrated with the idea of an Anthropocene. In 2002, Crutzen argued that the influence of human actions on the Earth's natural systems is profound enough to constitute a new geological epoch, different from the previous Holocene. Traditionally, the designation of geologic epochs is determined by investigations into Earth's rock layers, what they contain, and what that tells us about past environments. Since the Industrial Revolution, global population increases, resulting pollution, and the decimation of species (Kolbert 2014) may be the equivalent of environmental changes in geologic time. Therefore, many scholars and scientific organizations have adopted the Anthropocene perspective. The key premise that many planetary boundaries have been, or are on the verge of being, transgressed due to human actions makes the concept complimentary to the Anthropocene. From a planetary boundaries' perspective, the objective is to stay in Holocene conditions, although that seems increasingly unlikely. As social scientists point out, though, geographies of risk in the Anthropocene are complex. Resilience and vulnerability vary greatly based on location and income. Therefore, other holistic perspectives like 'planetary just transitions' and 'planetary ethics' conclude that policies must be both social and environmentally just with obligations to all groups, present and future, and incorporating the knowledge and resilience of indigenous societies (Stevs & Felli 2000; Valadez 2015; Ford *et al.* 2020).

Nearness, farness, and the diffusion of research

The adoption of planetary boundaries is, in a Kuhnian (1962) sense, an extension of current normal science rather than a scientific revolution. Nevertheless, the planetary boundaries concept is, in the context of diffusion, a new idea associated with uncertainty. For scholars exploring a new idea, it is advantageous to embrace the perspective of renowned individuals who originally adopted, or even invented, the new concept. Traditional diffusion theory postulates that a diffusion process disseminates from a smaller group of individuals (innovators), and spreads among a larger group (early adopters) who quite often know each other, before broad-based adoption occurs (Rogers 2003). This process resembles an s-shaped curve, with increasing adoption over time, followed by the tapering off, or saturation, of adoption.

Spatially, diffusion is also influenced by a neighborhood effect—when the immediate socio-cultural environment shapes people's actions, attitudes, and propensity to adopt an idea. Information diffuses more easily among people and places in relative proximity, and such flows decrease with distance (Brown 1981; Morrill *et al.* 1988). However, the use of the internet and the 'collapse of space' has allowed for more rapid flow of information, which potentially limits the neighborhood effect. In the context of planetary boundaries, the (global) scientific community that utilizes the concept is 'the neighborhood.'

In addition to the positivist tradition that treats space as having Cartesian properties—the world's surface as a coordinate system—geography also has a humanistic tradition recognizing that human awareness and perception is powerful in understanding social phenomena (Ash 2020). Thus, spatiality—the qualities of space, including both physical arrangements and the way it is experienced and perceived—matters as physical space does not always capture social practices and norms. Space is therefore qualitative, rather than simply locations on a map, which structures everyday human activity. Cartesian understanding of space and distance is not how the world is understood on a personal level. Drawing on German philosopher Heidegger, people can feel near or far from phenomena independent of concrete location (Rickert 2024). Some things are 'epistemologically near' which are things we are conditioned to know and understand, while things 'epistemologically far' are seen as more irrelevant and foreign. The farther away things are, the more difficult it is to understand them. What is physically far can be near us, yet what is physically near is still relevant because the collapse of space is an incomplete process (Meijas 2015). Heidegger's nearness and farness are relevant to scientists' understanding of planetary boundaries as a concept and, ultimately, how to conceptualize environmental crises.

Collaborative environments, such as research, are examples of endeavors that may transcend distance. Knowledge is created and shared in networks, which may or may not be localized. Proximity has been shown to enhance research collaborations on a national level in Great Britain (Katz 1994) and China (Liang & Zhu 2002), which supports the localized network idea. But as scientific research involves tacit knowledge production at a lower level than in industrial innovation and research and development, it also allows for long-distance collaboration (Healey *et al.* 2008). Much scientific knowledge aims to be generalizable and is therefore also global in scope. On the other hand, research sites have cartesian coordinates and data collection can be enhanced by proximity. Also, funding mechanisms often exist nationally and regionally (e.g., the European Union), which favors proximity.

Relating to nearness and farness, the Bogardus social distance scale measures the willingness of individuals to engage in social contacts (such as research) depending on the degrees of closeness they sense with other groups, such as based on nationality and ethnicity (Mather *et al.* 2017). For example, researchers in Southern Europe are more prone to engage in national collaborations while northwestern Europe tends to be more international. Also, language skills matter; Avdeev (2019) finds that linguistic commonalities among authors are a good predictor for research collaborations, as measured co-authored papers. These factors influence the spread of scientific concepts.

Methods: measuring the spread of the concept

The objective of this paper is to investigate the academic usage of planetary boundaries over time and space, and compare it to the growth of other sustainability concepts. The main data sources are three databases—Google Scholar, JSTOR, and Academic Search Premier (ASP)—which are used to investigate how much academic research has been published on planetary boundaries. The databases were selected based on their high level of prominence in academic research and that they have comprehensive coverage across disciplinary boundaries. Google Scholar is the broadest of the three as it is a search engine that captures a variety of publishing formats and scholarly disciplines. The downside is that its scope makes it unwieldy, and results are poorly organized. For greater precision, the traditional databases JSTOR and ASP were also used. The objective is not to capture every planetary boundaries publication; rather, to establish a sample that is manageable, yet substantial and robust. For that purpose, the above database selection was appropriate¹.

One limitation is that almost all research included in this study is in English. While over 90% of global research articles disseminated through leading academic indices are in English, and 75% of academic journals tied to such databases are published in English (Liu 2017; Giménez Toledo 2024), there is certainly relevant research published in other languages. It may appear in edited books and monographs, which for example are common outlets for research in human geography, or in policy documents and other influential forms of dissemination. Khanna and colleagues (2022) found over 25,000 multilingual journals, a majority from the Global South, that are largely absent from mainstream international academia. There are also peer-reviewed journals in other languages in the Global North, in which scholars choose to publish regularly as a way to engage with national scholarly communities and debates. Hence, it is important to acknowledge knowledge production beyond Anglophone scholarship.

For this paper, however, the first step involved using the phrase ‘planetary boundaries’ for a full-text search (conducted in October 2023). This provided a publication pattern from 2009 (when the first publication appeared) through 2022. The objective was to investigate if and how planetary boundaries have become more prominent in research over time. To collect more details about the scholars who utilize planetary boundaries in their research, the second step extracted a narrower set of research publications via JSTOR and ASP that contained country-level academic affiliation of the authors and the academic discipline they represent. The purpose was to investigate how widespread research on planetary boundaries is geographically and scholarly (in the natural sciences, social sciences, humanities, and so on). To generate a manageable sample size, I narrowed the search to abstracts only. For that, the search functionality of ASP and JSTOR is more useful than Google Scholar. Of the two, ASP yielded better results because, unlike JSTOR, it has html-based abstracts that are highly searchable. By limiting the search to abstracts, the data set captured articles where planetary boundaries play a relatively important role. The abstract-based search yielded 280 articles, predominantly from academic journals, but with some publications from popular press or book chapters. The results were screened for duplicates as well as articles that may not be about planetary boundaries, as defined here. The latter only resulted in the omission of one article (which concerned astrophysics rather than planetary boundaries in the Earth systems sense). The lack of misidentified articles suggests that any potential error using a basic search phrase method is minimal. In other words, the method captures research it intends to capture. To determine which articles among the 280 are most important, citation metrics from Google Scholar were recorded.

Subsequently, to contextualize the growth trend of planetary boundaries research, a temporal comparison was made with two established sustainability concepts—Anthropocene and ecological footprint. As argued above, these two concepts are related to planetary boundaries and as database search terms within quotation marks, they reliably yield robust results that do not include scholarly material about other phenomena. In contrast, tests using ‘limits to growth’ or ‘degrowth’ yielded complex and extensive search results in need of significant manual sorting and were therefore not included. The method was replicated as a full-text search on ‘Anthropocene’ and ‘ecological footprint,’ although extended backward in time to 2002 (for Anthropocene) and 1994 (for ecological footprint). The growth of scholarly adoption of those concepts was then compared to planetary boundaries.

Lastly, a content analysis of the 280 abstracts was conducted. I developed a three-part content categorization with the objective of investigating how the researchers used planetary boundaries. More specifically, articles are categorized as:

- Level A. Articles that have a very high level of engagement with the concept in that they are fundamentally about the planetary boundaries; they assess, critique, or refine the concept; or they compare it to other concepts.
- Level B. Articles with a medium level of engagement that use planetary boundaries as a major theoretical framework in an investigation of a specific environmental topic; or discussing planetary boundaries as one among other equally important concepts.
- Level C. Articles with a relatively low level of engagement with planetary boundaries; the concept plays a modest role for the stated research question and is primarily used as a background idea.

Diffusion of Planetary Boundaries

Growth of the concept

References to planetary boundaries increase dramatically over time. The cumulative search results of Google Scholar, which captures all types of academic or academic-related publications, was 40,377 during the study period. The steady increase annually from 2009–2022 ranges from 75 works that referenced planetary boundaries in 2009 to 7,760 in 2022 (Figure 2). The pattern indicates a growing and even accelerating prominence of the concept. As the content analysis of the aforementioned 280 abstracts only included one article that was misidentified as referring to planetary boundaries, the larger Google Scholar data set is also likely to contain search results that are overwhelmingly about planetary boundaries.

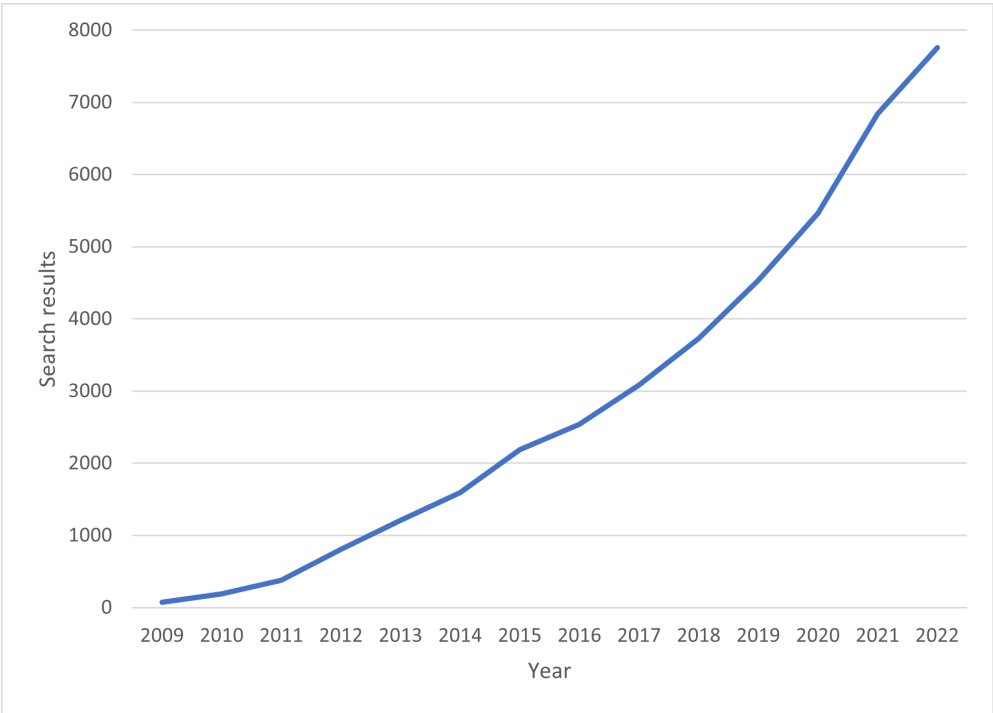


Fig. 2. Search results for ‘planetary boundaries’ from Google Scholar, 2009–2022.

Academic Search Premier, based on a full-text search on ‘planetary boundaries,’ shows a similar growth pattern (Figure 3). The steady increase (from five search results in 2009 to over 200 at the end of the study period) is typical of an early stage of diffusion of successful ideas—the acceleration phase in the s-curve of adoption of ideas. The ASP trend line is less regular than Google Scholar, which is possibly a result of a smaller data set. Compared to the more than 40,000 works about planetary boundaries in Google Scholar, the more narrowly curated ASP only captured 1,214 articles. However, well-designed scholarly databases include the most significant publications, as well as a strong emphasis on research articles in academic journals, compared to the ‘wide net’ approach of Google Scholar. What complicates the straightforward growth pattern, however, is that the JSTOR database (also shown in Figure 3) deviates from the other two data sets as articles about planetary boundaries peak in 2017 and then decline. The reason for the discrepancy is not clear. The total number of JSTOR articles is similar to ASP, 1,275 versus 1,214, although no analysis was conducted whether the two data sets included the same or different articles.

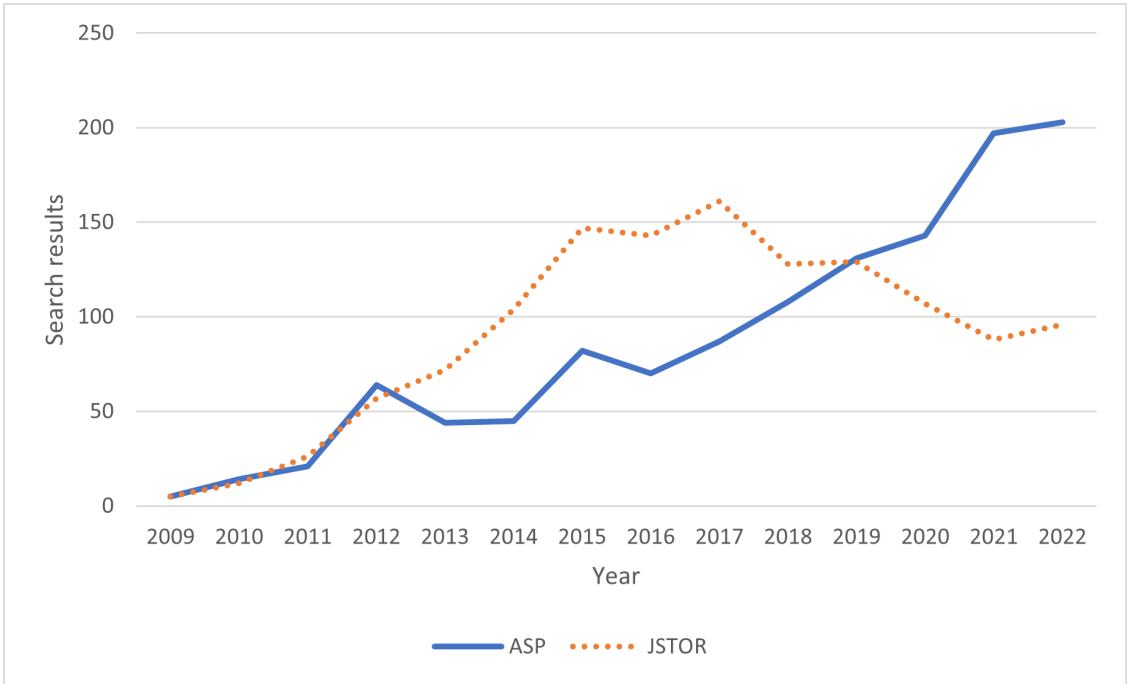


Fig. 3. Search results for ‘planetary boundaries’ from Academic Search Premier and JSTOR, 2009–2022.

Penetration of planetary boundaries into different academic disciplines

The next question concerns to what extent the planetary boundaries concept has been adopted by scholars in other academic traditions than in the Earth sciences, where it originated. The answer is that the concept is truly widespread. This determination is derived from the abstract-only data set from ASP and JSTOR.

The academic belonging of authors is based on their affiliation, as listed in each article. First, affiliation on the departmental level was recorded; subsequently, specific academic disciplines were reduced to 12 broader academic categories (e.g., political science and sociology are considered social sciences) and four non-academic categories. If no disciplinary belonging was listed (e.g., only a university), affiliation is considered ‘unknown.’ Moreover, authors occasionally list multiple affiliations, such as holding appointments at two universities. In such cases, only the first affiliation is used. Only

affiliations listed in the articles were considered; no attempt was made to assign academic affiliation through other sources. While some articles are single-authored, a majority have multiple authors; especially in the sciences, articles can have up to 30 authors. While the data includes only 280 articles, the research collectively represents the work of more than 1,000 scholars.

By academic convention, the first author of a publication is assumed to have made the most important contribution to the research. After that, additional authors contribute progressively less. This system has to be taken into account when assessing the importance of different scholars (and the academic discipline they represent) in research on planetary boundaries. The method to do so is Zipf's Law, which is a mathematical expression employed in natural and social sciences to assign proportionality of things relative to their rank. It has previously been used in studies that quantify scientific output and collaboration (Perc 2010; Krawczyk & Malarz 2023). The progression is expressed as $1/n$, where n equals the position a researcher has in the publication, a.k.a. the rank size rule². Thus, the first author of each article is assigned a value of 1, the second author 0.5, the third author 0.33, the fourth 0.25, and so on.

Figure 4 shows that the adoption of planetary boundaries is widespread among academic disciplines. More than a quarter of the researchers represent natural sciences (depicted in blue). 'Sustainability and environmental studies' (12%, rank-adjusted) are scholars from interdisciplinary academic units that focus explicitly on sustainability or the environment. For example, affiliation with the Stockholm Resilience Centre is placed in this category. The center has been important in the propagation of planetary boundaries, although only 15 of the 280 articles include one or more Stockholm Resilience Centre affiliated authors (in all, there are 30 such authors in the data set). That conclusion suggests that the concept is widespread beyond an 'echo chamber' of directly interconnected researchers. The 'Environmental sciences' category, with 13% of the scholarly output on planetary boundaries, are natural sciences that methodologically tends to be field research-based and have an overt focus on the environment (e.g., biology, physical geography, Earth science, climatology, oceanography), while the 'Other sciences' category (4%) include fields such physics, computer science, mathematics, and chemistry, with a lesser emphasis on environmental field research.

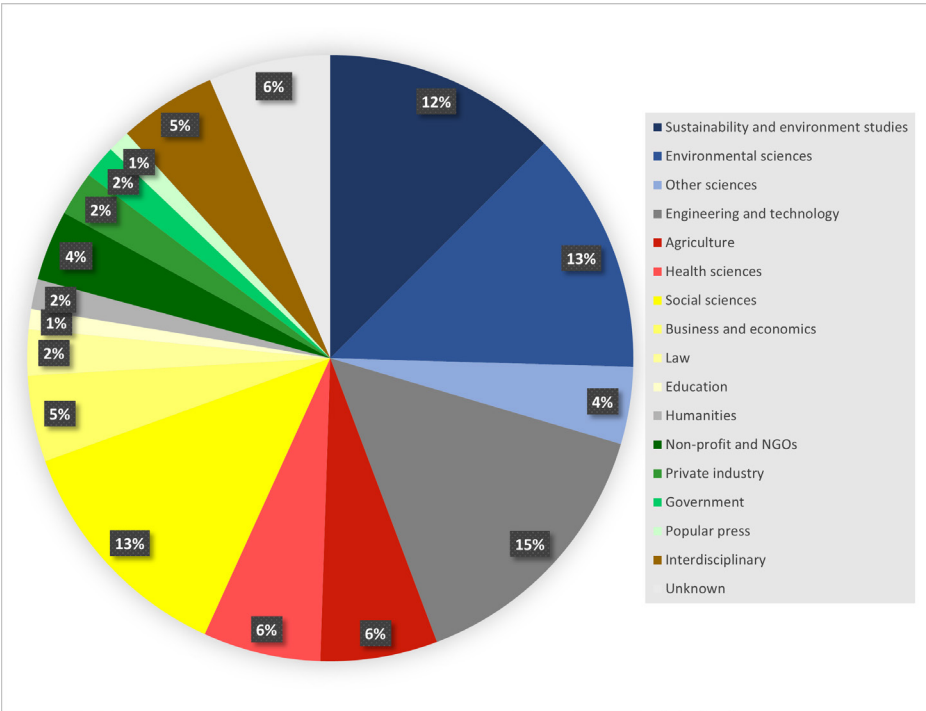


Fig. 4. The adoption of planetary boundaries by academic discipline.

Perhaps surprisingly, 'Engineering and technology' occupies the individually largest share of planetary boundaries research, as 15% of the research is derived from that field. Common examples include chemical engineering research on alternative fuels and chemical industry processes. Research related to manufacturing, such as the auto industry, biotech applications, and energy systems, also plays an important role. One journal in particular (*Journal of Clean Production*) is a common outlet for research on planetary boundaries in engineering. Agriculture and plant sciences, as well as medical and public health research, make additional and substantial contributions to planetary boundaries. The two categories are interrelated through research on diets, food, and nutrition (therefore visualized together in red in Figure 4). Particularly agriculture plays a key role in the use and management of global natural resources and is thus central to the nine systems of planetary boundaries. This is reflected in the data with substantial research on plant agriculture, livestock, and soil quality.

Figure 4 also shows that the social sciences are almost as important an adopter of planetary boundaries as the natural sciences (23% of research comes from social science and related fields; in yellow). Research in political science (especially public policy), global studies, sociology, planning, and human geography have made important contributions. For example, themes in geographic research include spatial patterns of sustainable development, knowledge production, water resources, and bioenergy and land use. Articles by geographers have been published in geography-specific journals (*Geographical Research*, *Geographical Compass*, *Antipode*), geography-related journals (*Environment and Society*), geoscience journals (*Journal of Geophysical Research*), or broad science journals (*PLOS One*). Of particular note is six articles by British geographer Noel Castree, which assesses geography's contribution to planetary boundaries research. Although not included in this study, at least one article in *Fennia* references planetary boundaries, in the context of green (de)growth (Halonen 2023).

Professional programs of the social sciences are particularly represented by business and economics, often publishing their planetary boundaries research in *Ecological Economics*. Legal scholars are interested in understanding how planetary boundaries can be applied in international and national legislation, corporate law, and the protection of indigenous people rights. Researchers outside academia also contribute to research on planetary boundaries, from non-profit and non-governmental organization sectors (4%), government (2%), and corporations (2%). A few citations from popular press sources were captured by the otherwise academically focused ASP and JSTOR databases, and an additional 5% of the research comes from interdisciplinary research units, which is another indicator of the broad adoption of the concept.

The geographic diffusion of planetary boundaries

The 280 articles from ASP and JSTOR also show the geographic origin of the researchers. The same method was used—by affiliation and the rank size rule method to quantify the relative contribution of multiple authors. National origin of researchers was not used, only academic affiliation (e.g., any researcher employed by the University of Oxford was coded as 'United Kingdom'). The result shows a distinct geographic pattern. European countries, as marked in blue in Figure 5, make up approximately two-thirds of research contributions. More specifically, there is a concentration in western and northern Europe. United Kingdom is the leading adopter of planetary boundaries (13% of affiliations), closely followed by Sweden (12%). The latter is a result of the concept originating at the Stockholm Resilience Centre. Approximately half of the Swedish citations are from scholars affiliated with that research institute. In general, the use of planetary boundaries is particularly strong in the Nordic countries (light blue shading), as both Finland and Denmark appear prominently in Figure 5. Additional European research often takes place in Western European countries such as Germany, Switzerland, and the Netherlands. The contribution from United States is lower than expected considering the prominence of U.S. academic research in general. Only 8% of planetary boundaries research originated in United States. Australia, less than a tenth in size, published almost as much planetary boundaries research as the U.S. Similarly, China—the quantitative leader in general academic output (Hyland 2023)—only published 3% (as part of the Asia and Oceania category in Figure 5) of planetary boundaries articles. A smaller amount of research originated in Latin America, Africa, and other world regions. Explanations for these observations are offered in the discussion section.

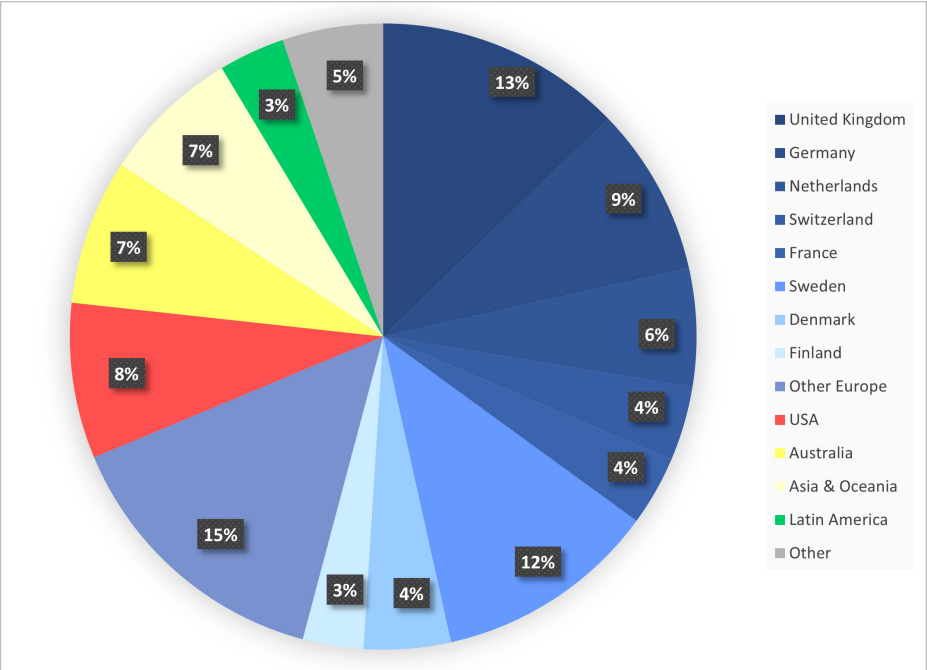


Fig. 5. The adoption of planetary boundaries by geographic location of researchers.

Citation count

Not all publications contribute equally to the diffusion of a concept. The common way to assess relative importance is how often an article is cited by others. Among the 280 articles, the mean number of Google Scholar citations in the dataset is 120, although there is a very high degree of variation, which affects the mean. The median citation count is, in fact, only 18. The aforementioned Rockström and colleagues (2009) that introduced the planetary boundaries concept emerges as a key publication with 7,469 citations. It is the second most cited article on planetary boundaries after Steffen and colleagues (2015), which was published in the leading journal *Science* and had 11,239 citations at the time of data collection. Steffen and colleagues proposed an update to the planetary boundaries framework and how it should integrate new scientific advances, emphasized the importance of biophysical interactions across spatial scales, and added a two-tier approach with core-status assigned to the most important boundaries. The high degree of circulation of the article effectively diffused these extensions of the concept.

The top two articles had co-authors affiliated with the Stockholm Resilience Centre. Of the 10 most cited articles, four come from the Centre, which has been important to spread the concept, especially during the early years of 2009–2012. However, there are other points of diffusion, such as the third most cited article Liu and colleagues (2015) which was also published in *Science* and noteworthy because it is authored by 11 U.S.-based scholars. As a Level C publication (see ‘The usage of planetary boundaries’ section below), the article emphasizes sustainability in general, and how environmental challenges are often addressed separately, yet these interconnected systems should be managed in an integrative way, and the planetary boundaries framework is one way to do so. For diffusion in the social sciences and economics, the journal *Ecological Economics* plays an important role; its articles (19 in all) often had a citation count in the 100-300 range.

Planetary boundaries growth compared to other sustainability concepts

To assess the planetary boundaries’ path of adoption compared to other sustainability concepts, a search on ‘Anthropocene’ and ‘ecological footprint’ using Google Scholar was compared to the search results conducted for planetary boundaries (previously visualized in Figure 2). The temporal start point varies as the three concepts emerged at different times. The first year of the ecological footprint is 1994, while Anthropocene dates from 2002. All three concepts followed a trajectory of increasing attention on a year-by-year basis. In 2022, the ecological footprint yielded 13,100 search results and Anthropocene 39,800, which can be compared to 7,760 for planetary boundaries. Planetary boundaries are still lagging behind the other concepts, but as the most recent among the three, that is expected.

The Anthropocene has a faster growth trajectory than the ecological footprint and surpassed it, as measured by search results, in 2014. The adoption of planetary boundaries is tracking the faster path of Anthropocene rather than the ecological footprint. Figure 6 compares the three concepts from Year 1 to Year 14, where Year 1 indicates the first time the concept appears (1994, 2002, 2009, respectively). The trend lines show the similarities between Anthropocene and planetary boundaries, although the former accelerated more quickly after approximately a decade. It is possible that the slower trajectory of the ecological footprint is due to a smaller global academic world in the 1990s; hence fewer search results may be expected then. However, that explanation is challenged by how this flatter growth trend only extends until 2020. After that, there is a renewed interest in the ecological footprint concept from 2020–2022, with a 47% increase in search results during the last two years.

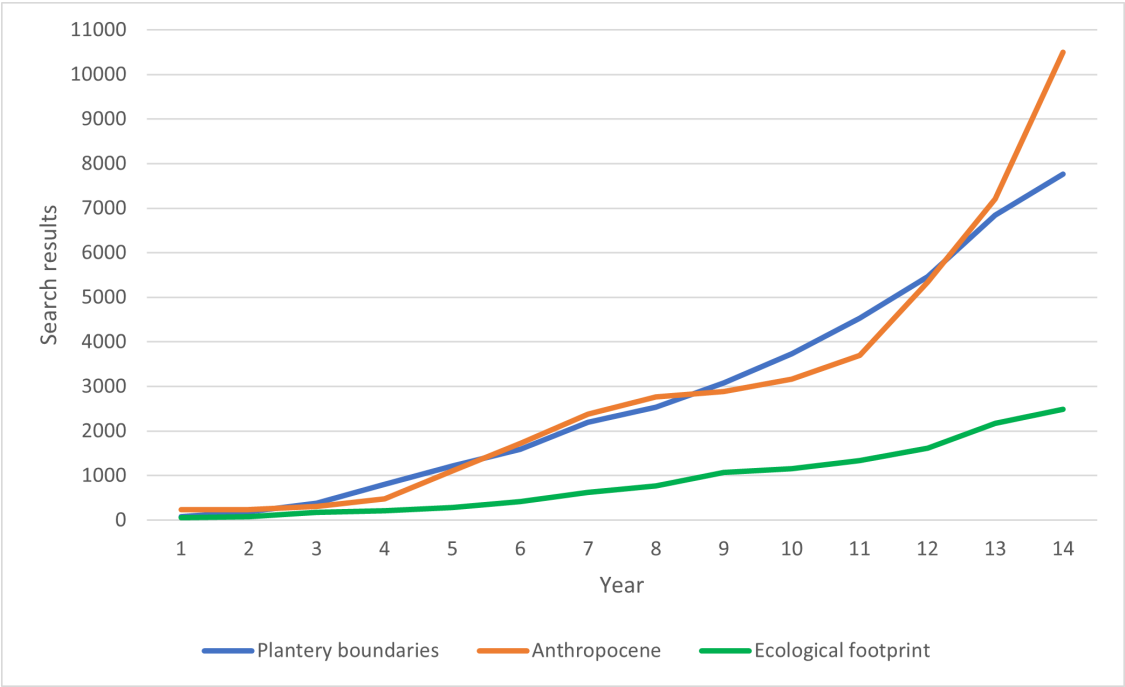


Fig. 6. Google Scholar search results of ‘Anthropocene,’ ‘ecological footprint,’ and ‘planetary boundaries’ from year of conceptual inception.

Using the smaller sample size Academic Search Premier (full-text search), results indicate that planetary boundaries actually outperform the other two concepts during the first nine years. Subsequently, Anthropocene enters an acceleration phase, which was also evident in the Google Scholar data. The ecological footprint growth trend is similar to planetary boundaries, but with fewer absolute number of articles. During the last decade, the pattern of growth for Anthropocene and planetary boundaries is faster than the ecological footprint. Much like the Google Scholar results, though, the ecological footprint, which plateaued around 2009–2019, has had a resurgence in recent years. However, its overall popularity is lower than the Anthropocene and similar to planetary boundaries.

The usage of planetary boundaries

Lastly, a content analysis of the ASP and JSTOR abstracts investigate how researchers incorporate planetary boundaries into their research, utilizing the three levels introduced in the Method section.

Level A

A smaller number of articles (31) were designated as Level A, articles with a very high level of engagement with the concept. In such articles, planetary boundaries play a dominant role. Typically, they assess, critique, or refine the concept; or they compare and contrast it with other concepts.

The most common engagement is when planetary boundaries are integrated with a second (or occasionally a third) concept. The objective can be to strengthen the planetary boundaries framework and to make it more robust, or to compare and contrast how different concepts address environmental problems. This includes concepts such as life cycle analysis, the UN sustainable development goals, ecological footprints, and the UN human development index. At times, article authors develop a new framework as an outcome of a conceptual merger. The purpose of such research is to advance new or improve existing conceptual or theoretical models. For example, Baum and Handoh (2014) suggest that global catastrophic risk models, which emphasize threats to human societies, can be integrated with planetary boundaries into a unified conceptual framework.

The ways in which planetary boundaries are operationalized matter. Hjalsted and colleagues (2020) discuss how to operationalize planetary boundaries as a tool for decision-making support. The aforementioned integration of two or more concepts also aims to improve their usefulness from a policy-making perspective. Policy advances can be on different scales, from regional entities like the European Union integrating planetary boundaries into their policy documents, to calls for using planetary boundaries in international law (Fernández & Malwé 2019). In fact, the scale issue looms large in much analysis of planetary boundaries. There is a need for local particularities to be recognized further (Drees *et al.* 2021). For example, water management must take place on local, regional, or watershed levels as thresholds, a key feature in planetary boundaries, loose much of their relevance on the global scale (Bjørn *et al.* 2020). At the same time, spatial interactions are important; e.g., the virtual water concept, which recognizes that 'hidden' water is used throughout the entire production chain of goods and services and indirectly by end consumers somewhere else in the world.

Some Level A articles utilize the case study method. This is common in agriculture-related research, from livestock as a key driver in transgressing planetary boundaries to water use in vegetable farming. Meta-analyses show how agriculture affects all of the nine boundaries, while other articles narrow the analysis to fewer boundaries. Occasionally, research rejects elements of the planetary boundaries framework all together. Such as the ontological critique of the concept by Hanekamp (2016) who calls the comprehensive understanding of safe operating spaces utopian and unworkable. Other critiques focus on individual boundaries (such as chemical pollution) as too imprecise, and they cannot be represented comprehensively as one planetary boundary (Persson *et al.* 2013). In sum, the type of research embodied by Level A articles plays an outsized role in generating knowledge; yet, quantitatively fewer research articles tend to be of this character.

Level B

A significant number of articles (79) use planetary boundaries on Level B, a medium level of engagement with the concept. In this type of research, planetary boundaries, focusing on everything from a single boundary to all nine, contribute a major theoretical framework in the investigation of specific environmental topics. One approach is to calculate the parameters of staying within the boundaries, such as changes to diets, agricultural systems, reduction in emissions, or through processes such as corporate sustainability reporting (Erlandsson *et al.* 2023). For example, Ehrenstein and colleagues (2020) employ planetary boundaries to evaluate the supply chain of hydrogen as a sustainable transportation fuel. On the other hand, some research suggests that specific economic activities contribute to the transgression of planetary boundaries. Other investigations focus on social policies, such as universal basic income or right-to-food (Heesterman 2017; Büchs 2021) and what the implications are for planetary boundaries. Much like A level articles, scale plays an important role where local and regional outcomes are investigated.

Other Level B articles focus more explicitly on planetary boundaries as a topic of research, but only as one concept among others. Articles on life cycle analysis are especially numerous where authors argue that planetary boundaries should be included in life cycle analysis, but in a subservient rather than a leading role. Another concept of relevance is Absolute Environmental Sustainability Assessment—a method that determines whether a product, process, or system is environmentally sustainable—by comparing environmental impacts to established planetary boundaries (Guinée *et al.* 2022). To advance policy, some articles ‘translate’ boundaries to needed emission reduction targets, or investigate the potential of regional green policies to stay within safe operating space (Tilsted *et al.* 2021). On the global scale, research redefines sustainable development to exist within planetary boundaries or investigate the United Nations’ millennium goals through the lens of planetary boundaries (Folke *et al.* 2011). Most Level B research tends to be empirical rather than conceptual, but some research addresses how planetary boundaries fits into degrowth theories or the Anthropocene (Castree 2014).

Level C

Most articles (182) are classified as Level C where the concept plays a modest role for the research question in the article. Here, planetary boundaries are used as a background concept. For example, Cash-Gibson and colleagues (2023) develop a conceptual framework for sustainable well-being in cities, but planetary boundaries are only a background idea that supports the main premise, urban sustainability. Authors may conclude that their study indicates the staying within boundaries or (more frequently) transgressing them. Such conclusions are rarely based on the original research, a proposition that is quantitatively assessed; rather, deduced from secondary sources. Topics of research among the Level C articles largely mirror those on the B-level, such as food systems, livestock and plant-based agriculture, dietary impacts, soil and nutrients, and bioenergy. A common type of application of planetary boundaries can be found in Alloul and colleagues (2019, 138), who preface their research with “nutrient losses in our food chain severely surpass our planetary boundaries” but subsequently employ methods from bioscience engineering to their project of using wastewater for animal feed. The usage of planetary boundaries only supports the ‘big picture’ relevance of the study.

A surprisingly large number of research articles deal with conceptual issues, including ‘competing’ theories to planetary boundaries, such as sustainable development goals, ecological footprints, degrowth, and the Anthropocene. In these cases, planetary boundaries do not occupy a leading role; it is one among many concepts under scrutiny, or it is a way for authors to frame their research around an important and increasingly accepted concept rather than engage with, challenge, or move planetary boundaries thinking forward. Water resource issues, environmental governance, and industrial processes also loom large. The application of new technology in fields such as energy and transportation is sometimes portrayed as solutions to stay within the boundaries. The larger number of research articles on Level C signal the strength of the concept. It is commonly accepted to use planetary boundaries as a reference point in research that addresses environmental crises. It is a

natural development where planetary boundaries have diffused sufficiently so that researchers in multiple fields adopt it as a foundational principle to situate their research.

Discussion and conclusion

The planetary boundaries concept has emerged as highly inter-disciplinary. The data reveals that it is not just limited to the environmental sciences, but has been found to be useful to researchers in a wide range of fields, such as engineering, health, agricultural sciences, social sciences, as well as in the public and private sectors. Geographically, planetary boundaries tend to be Eurocentric. There is a distance effect in its adoption. The data shows a concentration of research near the hearth of the concept in Sweden. Researchers in Nordic and western Europe are most likely to contribute to planetary boundaries research. The adoption of the concept in North America has lagged behind. Grieger, Hill and Leontyev (2022) offer one insight as to why that is. Based on a survey of university chemists in the United States, they conclude that most faculty were unfamiliar with the planetary boundaries concept and its integration into course curriculums were correspondingly low. The reason for this may be that research networks play a role. Distance matter; one is more likely to hear about a concept when in proximity, or connections and collaboration among scholars are forged in proximity. This conforms to a geographic axiom referred to as the first law of geography—near things are more related than distant things (see Sui 2004). Here, that means places that are close tend to have similar cultural and political environments that make them likely to adopt similar ideas, such as planetary boundaries. At the same time, planetary boundaries exist beyond Cartesian space. The spatiality of nearness and farness based on how researchers have been socialized into understanding the planetary boundaries as an important concept, or alternately not recognizing its existence, may be equally important to patterns of diffusion. For example, geographically distant Australian researchers are more likely to engage with planetary boundaries than American researchers.

There are parallels in earlier studies that can explain differences between European and American scholarship. Tight (2007) states that higher education research in North America and elsewhere in the world are largely separate. Further, he concludes that higher education research in North America tends to be inward-looking. Journals in United States contain mostly research conducted by American scholars, citing domestic research, while journals based elsewhere in the world is more geographically diverse in authorship and citation patterns (Tight 2014). Both Akbaritabar and Barbato (2021) (also in higher education studies) and Morawska (2008) (in research on immigration and ethnicity) recognize that American and European research is thematically different, partly explained by different funding structures (e.g., European Union or state agencies). Kwiek (2021) also stresses the importance of the European Union in that its funding favors co-authorship from multiple countries—in fact, Europe is a world leader in international research collaborations—and under such circumstances the diffusion of knowledge spreads more easily within Europe. Kwiek also recognizes the role of geography: such collaborations are made easier in a relatively compact world region with high internal mobility. Current studies also indicate, which is of relevance to the planetary boundaries case, that greater interdisciplinary exchange of scientific knowledge tends to enhance diffusion (Yan 2015).

European countries are often at the forefront of applying climate change-related science in policymaking (e.g., Cifuentes-Faura 2022). European scholars' emphasis on planetary boundaries may be affected by the propensity for relatively progressive environmental policy-making, and vice versa. In fact, planetary boundaries have been incorporated into the European Union's legal framework, and even included in United Nations documents (Fernández & Malwé 2019). Recommendations by the UN may filter to local and national policy-making more effectively in Europe than in the U.S. (e.g., Agenda 21 and UN Sustainable Development Goals) which also influences the two-way relationship science and environmental policy.

What about the rest of the world? The results here indicate that scholars based in less developed countries are less likely to publish research on planetary boundaries. However, the databases used in this paper are English-language focused, which undoubtedly skew the results and underestimate contributions from places like China, Latin America, and non-Anglo Europe. Akim, Silva, and de Fario (2025) previously acknowledged that compiling planetary boundaries research via leading,

international databases omit studies published in non-English languages. At the same time, there is no easy way to address linguistic biases; in fact, it is common that research simply acknowledges that non-English research is omitted from the study (e.g., Salinas-Velandia *et al.* 2022; Pham *et al.* 2024). Some non-English language research is included in the Academic Search Premier and JSTOR databases, but only if the papers had an English-version abstract. The low level of Chinese research may be partly explained by that. European research from France, Switzerland, and Germany also publish in languages other than English, according to van Leeuwen and colleagues (2001), which can arguably be extended to scholarly work from countries like Spain and Italy, and likely underrepresented. As noted earlier in the paper, English dominates as the lingua franca of scholarly work, which means that the most effective diffusion of ideas are captured by the databases used in this paper. Yet, knowledge production through conceptual development is also accomplished elsewhere, but systematically devalued and disenfranchised through global linguistic conventions (Fregonese 2017; Kallio *et al.* 2021). Nevertheless, the dominance of European research over United States in this study is unlikely to be the outcome of a geographically skewed sample of articles, as all three databases employed are U.S.-based.

The planetary boundaries concept has been established as a significant framework to understand environmental change. Compared to the Anthropocene, planetary boundaries are not as widespread, yet following a similar growth trajectory. While Google Scholar and the specialized academic databases show slightly different results, the general conclusion is that Anthropocene experienced a take-off after approximately a decade. Planetary boundaries grow steadily, but not yet exhibiting the same accelerating pattern. The ecological footprint is more popular than planetary boundaries as of 2022, but may have plateaued (according to ASP) or experienced steady but modest growth (as suggested by Google Scholar). The different results could be explained by the narrower research article focus of ASP compared to Google Scholar. For example, the ecological footprint has pedagogical applications as it can be scaled from the global to the individual level. As such, it has become a mainstay in environmental science and sustainability textbooks and in environmental communication aimed at the public. Planetary boundaries may take different paths in the near future—a take-off, steady growth, or potentially falling out of favor.

Organizing articles from Level A-C show less research with a high level of engagement with the planetary boundaries concept and more research with a low level of engagement. This is logical as planetary boundaries have diffused sufficiently so that multiple academic fields have adopted it as a foundational principle for their research. Research included in this article advances the planetary boundaries concept in multiple ways: making it more scale sensitive rather than solely a global phenomenon, integrating it with other sustainability concepts, investigating how it can inform policy, and utilizing case studies to offer more details on staying within or transgressing boundaries.

There are multiple ways to further study planetary boundaries as a scientific concept. First, how are planetary boundaries used in scholarly work? This article has added to that understanding but additional content analysis is desirable. In-depth content analysis can explore the intellectual development of planetary boundaries, which is relevant to understand the concept's emerging role in the history of science. Such research would build on Biermann and Kim (2020), who investigated the influence of the planetary boundaries concept on key bodies of literature. Second, one can further explore the temporal dimensions of diffusion. How has the use of planetary boundaries spread geographically, and across academic disciplines, over time? The data in this research do not fully connect the temporal dimension of geographic and academic dispersion. Such knowledge is relevant as the time-space dimension is important to understand the spread of important ideas, either through the spatiality of nearness and farness or through classic diffusion processes. Third, network analysis can explore which articles and authors have been influential in the spread of planetary boundaries through connections in citations. The work of Valente (1995) on network analysis of diffusion processes, or tracing knowledge diffusion in science as modelled by Chen and Hicks (2004) are approaches that can supplement the descriptive statistics used here. Such research is relevant as it has the potential to understand the planetary boundaries' integrative role in bringing scientists from various academic backgrounds together to understand global environmental change. Fourth, following Biermann and Kim's (2020) observation that planetary boundaries research has suffered

from the lack of perspectives from the developing world, it is also possible that non-English research exhibits different patterns of diffusion compared to articles that are published in journals that circulate through leading indices. Khanna and colleagues (2022, 927) write that the “citation patterns [from excluded research in both the Global South and the Global North] need to be mapped to learn about how this work interacts beyond this set of journals.” For example, writing about planetary boundaries in a Finnish context positions the concept as part of a Finnish conversation related to national sustainability transitions, academic interdisciplinary debates, and societal debates. Hence, the concept becomes localized, interpreted, and used differently than in an international context. Fifth, how does the planetary boundaries concept inform public policy? Such previous research includes McLaughlin (2018), Zipper and colleagues (2019), and Li and colleagues (2020), but fruitful additional research may use qualitative case studies, such as the Amsterdam example in the introduction, which could provide richer and nuanced perspectives on how the connection between scientific concepts and policy developments are intertwined locally, regionally, and globally.

Notes

¹ There are other alternative or additional databases that could be used, such as the prominent Scopus. However, Scopus was not available at the time of research due to the lack of a subscription by my university.

² Arguably the best-known application of the rank size rule is to illustrate hierarchies of cities and their position in national urban systems.

References

- Akbaritabar, A & Barbato, G. (2021) An internationalised Europe and regionally focused Americas: a network analysis of higher education studies. *European Journal of Education* 56(2) 219–234. <https://doi.org/10.1111/ejed.12446>
- Akim, E. K., Silva, D. A. L. & de Faria, L. C. (2025) Trends and hotspots in public food procurement: exploring planetary boundaries and human needs in an integrative literature review. *Journal of Public Procurement* 25(1) 95–119. <https://doi.org/10.1108/JOPP-12-2023-0091>
- Alloul, A., Wuyts, S., Lebeer, S. & Vlaeminck, S. E. (2019) Volatile fatty acids impacting phototrophic growth kinetics of purple bacteria: paving the way for protein production on fermented wastewater. *Water Research* 152 138–147. <https://doi.org/10.1016/j.watres.2018.12.025>
- Ash, J. (2020) Post-phenomenology and space: a geography of comprehension, form and power. *Transactions of the Institute of British Geographers* 45(1) 181–193. <https://doi.org/10.1111/tran.12331>
- Avdeev, S. (2019) International collaboration in higher education research: a gravity model approach. Higher School of Economics Working Paper No. WP BRP 54/EDU/2019. <https://doi.org/10.2139/ssrn.3505886>
- Baum, S. & Handoh, I. (2014) Integrating the planetary boundaries and global catastrophic risk paradigms. *Ecological Economics* 107 13–21. <https://doi.org/10.1016/j.ecolecon.2014.07.024>
- Biermann, F. & Kim, R. E. (2020) 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 Resource* 45 497–521. <https://doi.org/10.1146/annurev-environ-012320-080337>
- Bjørn, A., Sim, S., Boulay, A.-M., King, H., Clavreul, J., Lam, W. Y., Barbarossa, V., Bulle, C. & Margni, M. (2020) A planetary boundary-based method for freshwater use in life cycle assessment: development and application to a tomato production case study. *Ecological Indicators* 110 105865. <https://doi.org/10.1016/j.ecolind.2019.105865>
- Brown, L. (1981) *Innovation Diffusion: A New Perspective*. Meuthen, London.
- Büchs, M. (2021) Sustainable welfare: how do universal basic income and universal basic services compare? *Ecological Economics* 189 107152 <https://doi.org/10.1016/j.ecolecon.2021.107152>
- Cash-Gibson, L., Isart, F. M., Martínez-Herrera, E., Herrera, J. M., & Benach J. (2023) Towards a systemic understanding of sustainable wellbeing for all in cities: a conceptual framework. *Cities* 133 104143. <https://doi.org/10.1016/j.cities.2022.104143>
- Castree, N. (2014) The Anthropocene and geography I: the back story. *Geography Compass* 8(7) 436–449. <https://doi.org/10.1111/gec3.12141>

- Chen, C. & Hicks, D. (2004) Tracing knowledge diffusion. *Scientometrics* 59(2) 199–211. <https://doi.org/10.1023/B:SCIE.0000018528.59913.48>
- Cifuentes-Faura, J. (2022) European Union policies and their role in combating climate change over the years. *Air Quality, Atmosphere & Health* 15(8) 1333–1340. <https://doi.org/10.1007/s11869-022-01156-5>
- Club of Rome & Potsdam Institute for Climate Impact Research. (2020) Planetary Emergency 2.0: Securing a New Deal for People, Nature and Climate. https://clubofrome.org/wp-content/uploads/2020/08/Planetary_Emergency_Plan_2.0-.pdf
- Crutzen, P. (2002) Geology of mankind. *Nature* 415(23). <https://doi.org/10.1038/415023a>
- Doughnut Economics Action Lab. (2020) The Amsterdam City Doughnut: A Tool for Transformative Action. <https://www.circle-economy.com/resources/the-amsterdam-city-doughnut-a-tool-for-transformative-action>
- Drees, L., Luetkemeier, R. & Kerber H. (2021) Necessary or oversimplification? On the strengths and limitations of current assessments to integrate social dimensions in planetary boundaries. *Ecological Indicators* 129 108009. <https://doi.org/10.1016/j.ecolind.2021.108009>
- Ehrenstein, M., Galán-Martín, Á. Tulus, V., & Guillén-Gosálbez, G. (2020) Optimising fuel supply chains within planetary boundaries: a case study of hydrogen for road transport in the UK. *Applied Energy* 276 115486. <https://doi.org/10.1016/j.apenergy.2020.115486>
- Erlandsson, J., Bergmark, P. & Höjer, M. (2023) Establishing the planetary boundaries framework in the sustainability reporting of ICT companies – A proposal for proxy indicators. *Journal of Environmental Management* 329 117032. <https://doi.org/10.1016/j.jenvman.2022.117032>
- Fernández, E. & Malwé, C. (2019) The emergence of the ‘planetary boundaries’ concept in international environmental law: a proposal for a framework convention. *Review of European, Comparative & International Environmental Law* 28(1) 48–56. <https://doi.org/10.1111/reel.12256>
- Folke, C., Jansson, Å., Rockström, J., et al. (2011) Reconnecting to the Biosphere. *AMBIO* 40(7)719–738. <https://doi.org/10.1007/s13280-011-0184-y>
- Ford, J., King, N., Galappaththi, E., Pearce, T., McDowell, G. & Harper, S. (2020) The resilience of indigenous peoples to environmental change. *One Earth* 2(6) 532–543. <https://doi.org/10.1016/j.oneear.2020.05.014>
- Fregonese, S. (2017) English: lingua franca or disenfranchising? *Fennia* 195(2) 194–196. <https://doi.org/10.11143/fennia.67662>
- Giménez Toledo, E. (2024) English dominates scientific research—here’s how we can fix it, and why it matters. *The Conversation*. 27.30.2024 <https://theconversation.com/english-dominates-scientific-research-heres-how-we-can-fix-it-and-why-it-matters-226198>. 26.11.2025.
- Grieger, K., Hill, B. & Leontyev, A. (2022) Exploring curriculum adoption of green and sustainable chemistry in undergraduate organic chemistry courses: results from a national survey in the United States. *Green Chemistry* 22 8770–8782. <https://doi.org/10.1039/D2GC02999E>
- Guinée, J., de Koning, A., & Heijungs, R. (2022) Life cycle assessment-based absolute environmental sustainability assessment is also relative. *Journal of Industrial Ecology* 26(3) 673–682. <https://doi.org/10.1111/jiec.13260>
- Halonen, M. (2023) Multiple meanings and boundaries of growth in shrinking regions in East and North Finland. *Fennia* 200(2) 120–136. <https://doi.org/10.11143/fennia.119537>
- Hanekamp, J. (2016) Unravelling the planetary boundaries discourse – scientism and utopian thought. *Journal of Contingencies and Crisis Management* 24(2) 119–122. <https://doi.org/10.1111/1468-5973.12103>
- Healey, P. G. T., White, G., Eshghi, A., Reeves, A. & Light, A. (2008) Communication Spaces. *Computer Supported Cooperative Work* 17 169–193. <https://doi.org/10.1007/s10606-007-9061-4>
- Heesterman, W. (2017) The right to food and the planetary boundaries framework. *Science Progress* 100(1) 5–24. <https://doi.org/10.3184/003685017X14858552487427>
- Hjalsted, A. W., Laurent, A., Andersen, M. M., Olsen, K. H., Ryberg, M., & Hauschild, M. (2021) Sharing the safe operating space: exploring ethical allocation principles to operationalize the planetary boundaries and assess absolute sustainability at individual and industrial sector levels. *Journal of Industrial Ecology* 25(1) 6–19. <https://doi.org/10.1111/jiec.13050>
- Hyland, K. (2023) Enter the dragon: China and global academic publishing. *Learned Publishing* 36(3) 394–403. <https://doi.org/10.1002/leap.1545>
- Kahn, M. (2022) What the controversial 1972 ‘Limits to Growth’ report got right: our choices today shape future conditions for life on Earth. *The Conversation*, 12.07.2022 <https://theconversation.com/what-the-controversial-1972-limits-to-growth-report-got-right-our-choices-today-shape>

- [future-conditions-for-life-on-earth-184920#:~:text=The%20MIT%20research%20team%20that,resources%2C%20industrial%20production%20and%20pollution. 26.11.2025](#)
- Kallio, K. P., Heikkinen, A. M., & Riding, J. (2021) Editorial: societal impact through lingual plurality *Fennia* 199(1) 1–4. <https://doi.org/10.11143/fennia.109358>
- Kallis, G., Kostakis, V., Lange, S., Muraca, B., Paulson, S. & Schmelzer, M. (2018) Research on degrowth. *Annual Review of Environment and Resources* 43 291–316. <https://doi.org/10.1146/annurev-environ-102017-025941>
- Katz, J. (1994) Geographic proximity and scientific collaboration. *Scientometrics* 31 31–43. <https://doi.org/10.1007/BF02018100>
- Khanna, S., Ball, J., Alperin, J. P., & Willinsky, J. (2022) Recalibrating the scope of scholarly publishing: a modest step in a vast decolonization process. *Quantitative Science Studies* 3(4) 912–930. https://doi.org/10.1162/qss_a_00228
- Kim, R. E. & Kotzé, L. J. (2021) Planetary boundaries at the intersection of Earth system law, science and governance: a state-of-the-art review. *Review of European, Comparative & International Environmental Law* 30(1) 3–15. <https://doi.org/10.1111/reel.12383>
- Kolbert, E. (2014) *The Sixth Extinction: An Unnatural History*. Henry Holt, New York.
- Krawczyk, M. & Malarz, K. (2023) Recovering Zipf's law in intercontinental scientific cooperation. *Chaos* 33(11) 111102. <https://doi.org/10.1063/5.0166696>
- Kuhn, T. S. (1962) *The Structure of Scientific Revolutions*. University Press, Chicago.
- Kwiek, M. (2021) What large-scale publication and citation data tell us about international research collaboration in Europe: changing national patterns in global contexts. *Studies in Higher Education* 46(12) 2629–2649. <https://doi.org/10.1080/03075079.2020.1749254>
- van Leeuwen, T. N., Moed, H. F., Tijssen, R. J. W., Visser M. S. & van Raan, A. F. J. (2001) Language biases in the coverage of the Science Citation Index and its consequences for international comparisons of national research performance. *Scientometrics* 51 335–346. <https://doi.org/10.1023/A:1010549719484>
- Li, M., Wiedmann, T., Liu, J., Wang, Y., Hu, Y., Zhang, Z. & Hadjikakou M. (2020) Exploring consumption-based planetary boundary indicators: an absolute water footprinting assessment of Chinese provinces and cities. *Water Research* 184 116163. <https://doi.org/10.1016/j.watres.2020.116163>
- Liang, L. & Zhu, L. (2002) Major factors affecting China's inter-regional research collaboration: regional scientific productivity and geographical proximity. *Scientometrics* 55(2) 287–316. <https://doi.org/10.1023/A:1019623925759>
- Liu, J., Mooney, H., Hull, V., Davis, S. J., Gaskell, J., Hertel, T., Lubchenco, J., Seto, K., Gleick, P., Kremen, C. & Li, S. (2015) Systems integration for global sustainability. *Science* 347 6225. <https://doi.org/10.1126/science.1258832>
- Liu, W. (2017) The changing role of non-English papers in scholarly communication: evidence from Web of Science's three journal citation indexes. *Learned Publishing* 30(2), 115–123. <https://doi.org/10.1002/leap.1089>
- Mather, D., Jones, S. & Moats, S. (2017) Improving upon Bogardus: creating a more sensitive and dynamic social distance scale. *Survey Practice* 10(4) <https://doi.org/10.29115/SP-2017-0026>
- McLaughlin, J. F. (2018) Safe operating space for humanity at a regional scale. *Ecology and Society* 23(2) 43. <https://doi.org/10.5751/ES-10171-230243>
- Meadows, D., Meadows, D., Randers, J. & Behrens III, W. (1972) *The Limits to Growth; A Report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books, New York.
- Meadows, D., Randers, J. & Meadows, D. (2004) *Limits to Growth: The 30-year Update*. Green Publishing, Chelsea.
- Mejias, U. (2005) Re-approaching nearness: online communication and its place in praxis. *First Monday* 10(3). <https://doi.org/10.5210/fm.v10i3.1213>
- Morawska, E. (2008) Research on immigration/ethnicity in Europe and The United States: a comparison, *The Sociological Quarterly* 49(3) 465–482. <https://doi.org/10.1111/j.1533-8525.2008.00124.x>
- Morrill, R, Gaile, G., & Thrall, G. I. (1988) *Spatial Diffusion*. Sage, Newbury Park.
- Perc, M. (2010) Zipf's law and log-normal distributions in measures of scientific output across fields and institutions: 40 years of Slovenia's research as an example. *Journal of Informetrics* 4(3) 358–364. <https://doi.org/10.1016/j.joi.2010.03.001>
- Persson, L., Breitholtz, M., Cousins, I., de Wit, C., MacLeod, M. & McLachlan, M. (2013) Confronting unknown planetary boundary threats from chemical pollution. *Environmental Science & Technology* 47(22) 12619–12622. <https://doi.org/10.1021/es402501c>

- Pham, L. T., Kumar, P., Dahana, W. D. & Nguyen, H. D. (2024) Advancing sustainable development through planetary health – a holistic approach to global health: a systematic review. *Environmental Science & Policy* 155 103709. <https://doi.org/10.1016/j.envsci.2024.103709>
- Raworth, K. (2017) *Doughnut Economics: Seven Ways to Think Like a 21st-century Economist*. Random House, London.
- Rees, W. (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. *Environment & Urbanization* 4(2) 121–130. <https://doi.org/10.1177/095624789200400212>
- Richardson, K., Steffen, W., Lucht, W., Bendtsen, J., et al. (2023) Earth beyond six of nine planetary boundaries. *Science Advances* 9(37). <https://doi.org/10.1126/sciadv.adh2458>
- Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F., Lambin, E., et al. (2009) Planetary boundaries: exploring the safe operating space for humanity. *Ecology & Society* 14(2) 32. <https://doi.org/10.5751/ES-03180-140232>
- Rogers, E. M. (2003) *Diffusion of Innovations*. 5th ed. Free Press, New York.
- Salinas-Velandia, D. A., Romero-Perdomo, F., Numa-Vergel, S., Villagrán, E., Donado-Godoy, P., & Galindo-Pacheco, J. R. (2022) Insights into circular horticulture: knowledge diffusion, resource circulation, one health approach, and greenhouse technologies. *International Journal of Environmental Research and Public Health* 19(19) 12053. <https://doi.org/10.3390/ijerph191912053>
- Steffen, W., Richardson, K., Rockström, J., Cornell, S., Fetzer, I., Bennett, E., et al. (2015) Planetary boundaries: guiding human development on a changing planet. *Science* 347(6223) 736–746. <https://doi.org/10.1126/science.1259855>
- Stavis, D. & Felli, R. (2000). Planetary just transition? How inclusive and how just. *Earth Systems Governance* 6 100065. <https://doi.org/10.1016/j.esg.2020.100065>
- Sui, D. (2004) Tobler's first law of geography: a big idea for a small world? *Annals of the Association of American Geographers* 94(2) 269–277. <https://doi.org/10.1111/j.1467-8306.2004.09402003.x>
- Tight, M. (2007) Bridging the divide: a comparative analysis of articles in higher education journals published inside and outside North America. *Higher Education* 53 235–253. <https://doi.org/10.1007/s10734-005-2429-9>
- Tight, M. (2014) Working in separate silos? What citation patterns reveal about higher education research internationally. *Higher Education* 68(3) 379–395. <https://doi.org/10.1007/s10734-014-9718-0>
- Tilsted, J. P., Bjørn, A., Majeau-Bettez, G. & Lund, J. F. (2021) Accounting matters: revisiting claims of decoupling and genuine green growth in Nordic countries. *Ecological Economics* 187 107101. <https://doi.org/10.1016/j.ecolecon.2021.107101>
- Valadez, J. (2015) Planetary ethics and the future of humanity. Paper presented at Yale University-Critical Theory Roundtable, October 2015.
- Valente, T. (1995) *Network Models of the Diffusion of Innovations*. Hampton Press, New Jersey.
- Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., et al. (2022) A planetary boundary for green water. *Nature Reviews Earth & Environment* 3 380–392. <https://doi.org/10.1038/s43017-022-00287-8>
- Yan, E. (2016) Disciplinary knowledge production and diffusion in science. *Journal of the Association for Information Science and Technology* 67(9) 2223–2245. <https://doi.org/10.1002/asi.23541>
- Zipper, S., Gleeson, T., Wang-Erlandsson, L., Porkka, M., Jaramillo, F., Gerten, D., et al. (2019) Operationalizing the freshwater planetary boundary for local to global water management and sustainability. *Geophysical Research Abstracts* 8(2) e2019EF001377. <https://doi.org/10.1029/2019EF001377>