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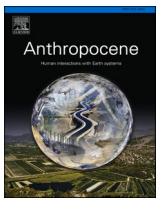

Geologic limitations on a comprehensive Anthropocene

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ABSTRACT

Following its advent as a concept, the Anthropocene has flourished as a new worldview in academic and public communities alike. Yet, the Subcommission on Quaternary Stratigraphy recently voted against formally ratifying the Anthropocene as an Epoch, pointing to the restrictive geologic framework, and highlighting the need for a globally represented and synchronous marker. In this Viewpoint, we utilize global bibliographic data, Google search data, IPCC authors, and the Global Climate Risk Index (GCRI) to examine the global diversity of the Anthropocene discourse by measuring academic interest and public engagement in the topic, while also considering the proportional influence, justice, and inclusivity of this discourse. We argue that the conceptual and geological frameworks of the Anthropocene share a complex and non-translatable relationship. Further, we urge reconsideration of geologically rigid definitions in the spirit of recognizing holistic identification of human impacts to the Earth System, while also addressing the gaps in global influence with this pressing concept. Last, we explore successful examples integrating disparate disciplinary perspectives to achieve greater understanding of the Anthropocene and discuss avenues for future directions in the areas of human-environment interactions, as well as environmental justice and equity.

1. Introduction

Earth's climate is changing at an unprecedented rate due to anthropogenic activities (IPCC, 2023). In the last century, humans have altered its every sphere: biosphere, hydrosphere, atmosphere, and lithosphere (Richardson et al., 2023). In 2000, scientists Crutzen and Stoermer first recognized that, because of anthropogenic activities, Earth's climate conditions were no longer contained within the known bounds of the Holocene epoch (Fig. 1), dubbing the new segment of Earth history the Anthropocene (Crutzen and Stoermer, 2000). The Anthropocene has subsequently become synonymous with anthropogenic climate change (Dalby, 2014; Marshman et al., 2019; Steffen et al., 2011). More broadly, academia has embraced the concept of the Anthropocene as a means of reframing scientific and philosophical perspectives on the role and impact of humans on Earth, as illustrated by nascent interdisciplinary journals such as *Anthropocene*, *Anthropocene Review*, *Anthropocene Science*, *Elementa: Science of the Anthropocene*, and others. In addition to academic interest in the topic, broader public interest also increased ca. 2000, as demonstrated by fiction works such as Roland Emmerich's movie *The Day After Tomorrow*, Kim Stanley Robinson's novel *Forty Signs of Rain*, and Michael Crichton's novel *State of Fear* (Fig. 1). In 2009, the International Commission on Stratigraphy created the Anthropocene Working Group (AWG), within the Subcommission of Quaternary Stratigraphy, to build a case for the consideration of formally ratifying the Anthropocene Epoch as a chronostratigraphic unit of geologic time (Fig. 1) ("Working Group on the 'Anthropocene' 2022).

Concurrent with the advent of the Anthropocene as a concept, international intergovernmental organizations and policies were created with the goal of mitigating the effects of the climate crisis. Inspired by the ultimately symbolic Kyoto Protocol, which in the end was primarily ratified by non-major emitters (e.g., did not include USA, China, or Australia), the Paris agreement, with virtually unanimous global support, went into effect in 2016 (Fig. 1) (UNFCCC, 1997). This agreement formalized a global consensus and commitment to the reduction of global emissions contributing to climate change (UNFCCC, 2015). Firmer geopolitical stances on climate change were subsequently taken, with the EU declaring a global state of emergency in 2019 and the IPCC6 stating unequivocally that anthropogenic impacts were causing global climate change in 2021 (Fig. 1) (IPCC, 2023). Although these agreements, declarations, and reports bear the semblance of global engagement, not all nations are represented equally (Ho-Lem et al., 2011; Sultana, 2023). Like anthropogenic climate change, as well as most 'global' scientific interests (Amarante et al., 2022; Hedding and

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Breetzke, 2021; Maas et al., 2021), the engagement with and impact of the Anthropocene can be expected to be heterogeneous and inequitable across the globe (Parks and Roberts, 2006).

In March 2024, it was announced that the Subcommission on Quaternary Stratigraphy, the ruling body over the AWG, had voted against the proposed formal ratification of the Anthropocene Epoch as an official unit of geologic time (Zhong, 2024). Partial reasoning for this rejection stems from the inherently limited view of the proposed Anthropocene Epoch on the global history of anthropogenic climate change (Witze, 2024). To be considered as a formal unit of geologic time, stratigraphic sections must be marked by global boundary stratotype sections and points (GSSPs). GSSPs are regulated by a strict set of criteria, in which the boundaries must be distinct and continuous, have a recognizable, unambiguous change in fossil content or geologic properties, include minerals for radiometric dating, and able to support global stratigraphic correlation ("ICS," 2022). Essentially, a GSSP represents globally occurring deposits from the same point in time (Gibbard et al., 2022). While the proposed Anthropocene does meet these requirements superficially, ratifying the proposed Anthropocene Epoch as a unit of geologic time could be to the detriment of broader interest in the Anthropocene (Witze, 2024).

In academic study, the Anthropocene has become a topic of interdisciplinary interest (Baldwin and Erickson, 2020; Birrell and Matthews, 2020; García-Juanatey and Steible, 2023; Jabot, 2022; Marriner et al., 2022; Simangan, 2020; Syvitski et al., 2020; Waters and Turner, 2022). The Anthropocene has evolved from its original meaning (Crutzen and Stoermer, 2000) to encompass a global and diverse range of expertises, fields, and backgrounds (Braje et al., 2014; Brondizio et al., 2016; Gibbard et al., 2022; Nichols and Gogineni, 2018). This Viewpoint aims to present evidence for the diversity of the Anthropocene discourse by measuring global academic interest and public engagement in the topic. As the Anthropocene is inextricably linked with anthropogenic climate change, we use climate risk vulnerability as a proxy of nations expected to be most affected during the Anthropocene. This analysis also aims to understand geographically how knowledge of the Anthropocene and climate change relates to policy-power and climate risk.

2. Methods

To explore the global diversity of Anthropocene discourse, as well as its academic and public inclusivity and equity, we assembled several datasets to serve as proxies of academic and public engagement, global policymaking influence, and global climate risk exposure. Our approach is somewhat unique in our combination of numerous sources of information, but generally follows published methodologies established in previous research relying on bibliometric, internet search, global climate change policy influence, and climate change risk metrics.

Bibliometric reviews are an informative means of gauging academic interest in a subject and how it has changed over time (Grandjean et al., 2011; Liu et al., 2011). Indeed, Web of Science, Google Scholar, Scopus and other bibliographic databases have increasingly been used to undertake comprehensive literature searches and meta-analyses (Ellegaard, 2018). To survey academic engagement in the Anthropocene, a systematic review of available literature was conducted on 25 January 2024. This review was undertaken with the Web of Science database, which includes helpful functions to categorize bibliographic documents by field. To gauge academic interest in the topic, the term "Anthropocene" was searched across titles, abstracts, and author keywords within the Web of Science database. Results were refined to exclude publications in the year 2024 and to include only the following document types: articles, books, book chapters, editorial material, and review articles. We opted to exclude conference proceedings, book reviews, and other document types, as these forms are not necessarily considered finalized publications depending on the field. The remaining 9314 documents were analyzed using the built-in "analyze results" function within Web of Science.

Google Trends (https://trends.google.com/trends/) is a publicly available tool that provides access to global Google search data beginning in 2004. The rationale for our use of Google Trends as a means of gauging global interest in the Anthropocene stems from published usage of internet searches to investigate topics of interest (Baram-Tsabari and Segev, 2011). Google Trends data have been increasingly used as a proxy of public interest and engagement with environmental topics at both global and more localized scales (Mccallum and Bury, 2013; Nghiem et al., 2016; Sherman-Morris et al., 2011; Żmihorski et al., 2013). Search data were used to measure global popularity and interest in the Anthropocene. Searches (2004–2023; the maximum time range) were filtered to include those relating to the "Anthropocene" as a search topic. Fortuitously, Google Trends provides results from similar search queries across languages based on the provided search topic term, providing a multi-lingual and global perspective of internet search interest. For example, if "apple" were the requested topic, the results would also include Spanish and French Google searches of "manzana" and "pomme", respectively. The results of each query on Google Trends are based on a representative and random sampling of all Google searches related to the specified term. Results were standardized (scaled from 0 to 100) to reflect national population and geography to better depict search popularity rather than strictly total search volume (Rogers, 2016). Resulting values represent the normalized interest in the search term compared to the total load of the population's Google searches in a given nation over the specified time period.

The goal of the Intergovernmental Panel on Climate Change (IPCC) is to provide global policy makers with current understanding of anthropogenic climate change. Therefore IPCC authorship is considered a proxy of global policymaking influence, and has been used to explore inequity of representation and inclusion (Ford et al., 2012; Ho-Lem

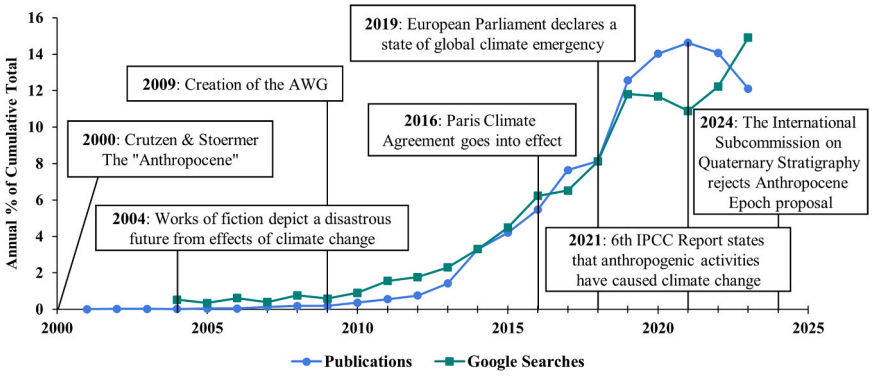

Fig. 1. The relative change of the global number of academic publications and Google searches each year. Relevant global events related to the Anthropocene and climate change are superimposed on the plot. Publication data spans from 2001 to 2023 and Google search data spans from 2004 to 2023.

et al., 2011). To this end, we consider IPCC authorship and influence in global climate policy as analogous to bargaining power in discussions of the Anthropocene. The number and country of origin of authors of all six IPCC assessment reports were included in this analysis (Tandon, 2023). IPCC authors were included to identify the nations with the most and least global influence within these reports.

Global Climate Risk Index (GCRI) data from 2000 to 2019 were included to identify which countries have been the most impacted by anthropogenic climate change (Eckstein et al., 2021). The GCRI, consolidated by the non-governmental and non-profit organization Germanwatch, reports the vulnerability of 180 countries to extreme weather events such as hurricanes, tropical storms, or flooding, but is not intended to consider less abrupt phenomena of climate change such as global warming or sea level rise. Countries with scores closest to 1 rank highest and are at a greater risk of extreme weather events or infrequent catastrophes. Additionally, the GCRI is restricted by the quality and variability of data available within and across countries (Eckstein et al., 2021).

3. Global academic and public engagement in the anthropocene

Our compiled dataset included 9314 publications from 143 countries and Google Trends data from 93 countries as proxies for academic interest and public engagement respectively. Both academic interest and public engagement with the Anthropocene has increased with relative synchronicity since the term's coining in 2000 (Fig. 1) (Crutzen and Stoermer, 2000).

Traditionally, the Anthropocene has been associated with the physical sciences, particularly geology as it refers to a proposed unit of stratigraphic time (Hamilton, 2016; Zalasiewicz et al., 2008). Surprisingly, only 14 % of the analyzed publications were categorized by Web of Science as belonging to the physical sciences (Fig. 2). The life science and biomedicine category contained the most publications at 37 % of the total, then social sciences at 26 %, art and humanities at 16 %, and technology at 7 %. Contrary to geology's field-specific outlooks or traditional thinking, most academic discourse related to the Anthropocene lies outside of both geology and the physical sciences. Field-typical publishing rates make this difference even more stark, as publication rates in the physical sciences tend to be faster than those in life or social sciences (Althouse et al., 2009).

Even though non-physical sciences are primary contributors to the Anthropocene's academic discourse, these fields are often left out of

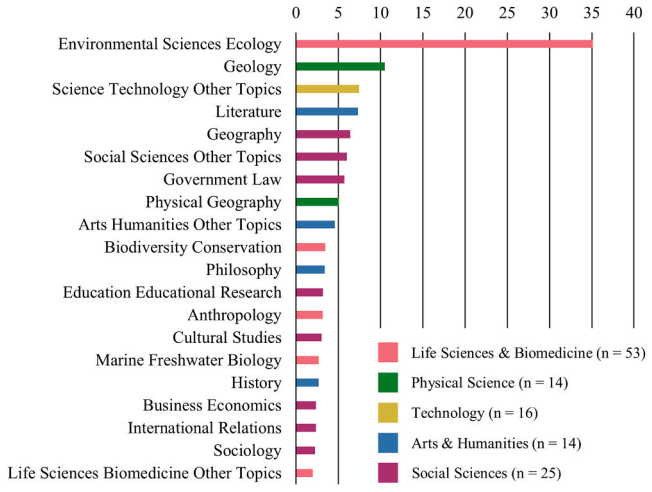

Fig. 2. Academic publications yielded in our Web of Science searches. Common research areas as defined by Web of Science graphed as the percentage of each category. Colors correspond to the Web of Science categories each research area fits within. Numbers next to each category are the number of areas within that category.

primary decision-making groups regarding its formalization, such as by the AWG. Discussions regarding the Anthropocene as a geologic term frequently lack interdisciplinary inputs or viewpoints, misrepresenting the general consensus of Anthropocene thinkers (Nichols and Gogineni, 2018). Future publications regarding the geologic framework of the Anthropocene, as well as discussions regarding its formalization, should strive to include viewpoints other than that of the physical sciences.

A recent study using data from the Gallup World Poll 2021/2022 collected from 125 countries found that globally, there is strong public support for pro-climate public and political action to combat global warming and climate change (Andre et al., 2024). Andre et al. measured the strength of respondent's personal convictions on climate action by proxy of their willingness to contribute 1 % of their annual household income to climate action. The study found that an individual's willingness to contribute decreases as the gross domestic product (GDP) of their nation increases (Andre et al., 2024). We found that, generally, countries with higher Anthropocene Google search proportions also had higher GDPs. Andre et al. also found that as an individual's willingness to contribute increases, their experienced average annual temperature and climate vulnerability also increases (Andre et al., 2024). Similarly, we found that as a nation's GDP increases, their climate vulnerability, as measured by their GCRI, also increases (Eckstein et al., 2021). We also found that as a nation's GDP increases, the number of UN members and number of Web of Science publications increases.

4. Global inequity and inclusion in the Anthropocene

The top five countries most impacted by climate change related extreme weather events from 2000 to 2019 were Puerto Rico, Myanmar, Haiti, Philippines, and Mozambique (Table 1) (Eckstein et al., 2021).Yet, these countries collectively account for only 1.57 % of total publications and 2.12 % of IPCC authors. Public engagement by proxy of Google searches was relatively low for the most affected countries as compared to the Global North (Fig. 3). Additionally, many smaller, more at risk countries lack sufficient data, as shown by blank cells in Table 1.

In contrast, Canada, which ranked 92 of 177 for global climate risk, accounted for 816 publications, 171 IPCC authors, and proportionally, 47 % of Canadian google searches were related to the Anthropocene. The most recent IPCC report recognized that in most cases, the countries that have contributed the least to climate change, through greenhouse gas emissions, land-use change, unsustainable energy consumption, and other mechanisms face disproportionately greater consequences than higher-contributing countries (IPCC, 2023). This phenomenon is also evident in our analyses of the Anthropocene (Fig. 3). Nations at a greater risk of adverse effects from climate change (Fig. 3.d) tend to have fewer Anthropocene-related publications Fig. 3(a), Google searches Fig. 3(b),

Table 1
Ten countries most impacted by extreme weather events caused by anthropogenic climate change from 2000 to 2019, and their respective number of publications, google searches, IPCC authors, and GCRI score. These countries account for a small percentage of each overall category despite experiencing the greatest impacts from climate change. Puerto Rico is not listed as a country or region by Web of Science. Blank cells had no data.

GCRI Rank	Country	WOS Publication Records	Google Searches (%)	IPCC Authors	GCRI Score
1	Puerto Rico		19	1	7.17
2	Myanmar	9			10
3	Haiti	1		1	13.67
4	Philippines	34	19	26	18.17
5	Mozambique	5		2	25.83
6	Bahamas	1		3	27.67
7	Bangladesh	20	6	12	28.33
8	Pakistan	22	11	11	29
9	Thailand	40	4	15	29.83
10	Nepal	14	12	11	31.33

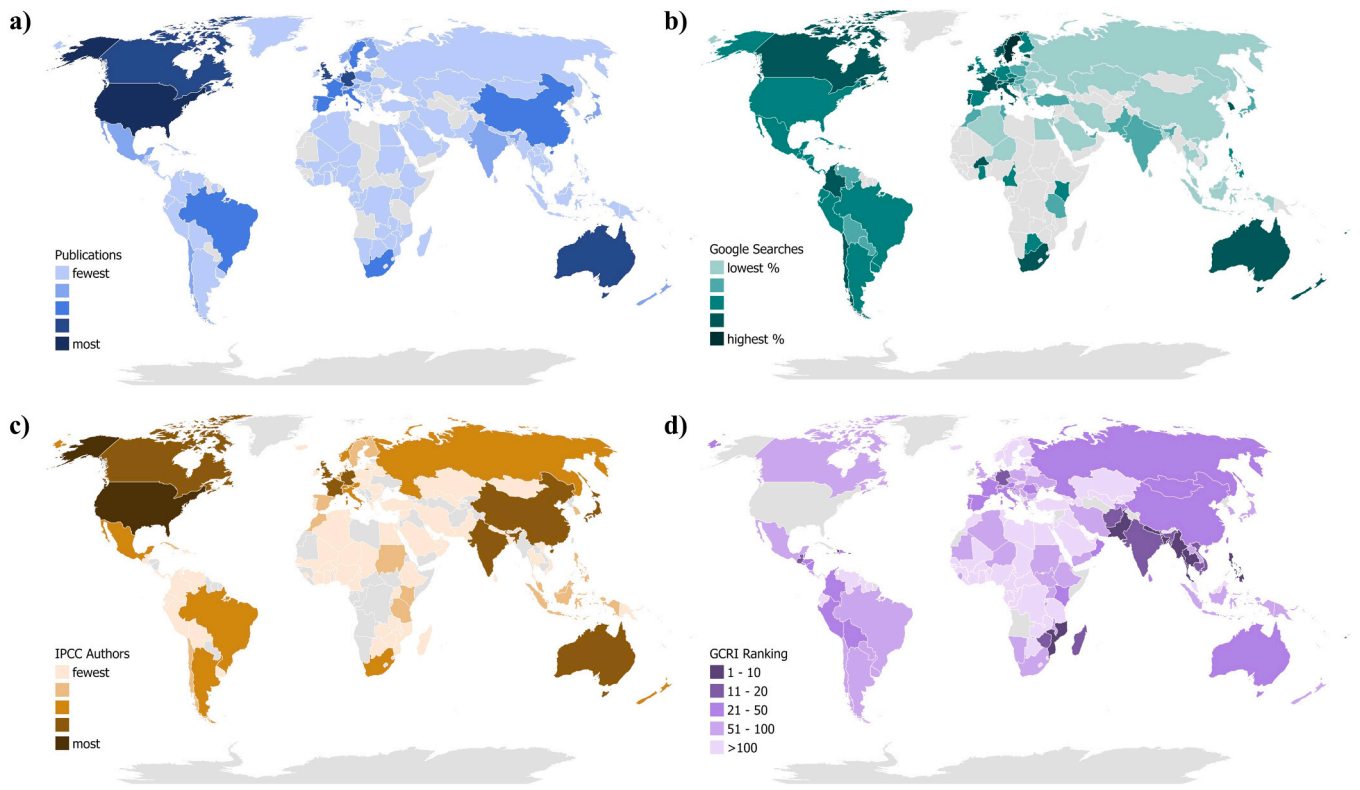

Fig. 3. Global map of: a) research interest as measured by the number of publications from 2001 to 2023 related to "Anthropocene" from Web of Science; b) public interest as measured by the normalized value of Google searches from 2004 to 2023 created by Google Trends (https://trends.google.com/trends/); c) political power as measured by the number of IPCC authors from all assessment reports; d) climate vulnerability from 2000 to 2019 shown as the global climate risk index (GCRI) calculated by Germanwatch (Eckstein et al., 2021). Countries in gray have no data.

and IPCC authors Fig. 3(d). Recalling that one reason for the rejection of the Anthropocene Epoch as an official unit of geologic time was its scientific and historical limitations (Witze, 2024), it is no surprise that authorship of Anthropocene publications is lacking in global representation.

Our analyses illustrate the disconnect between cooperative global engagement in climate mitigation policy, management, and interest, and the practical engagement of global communities in the Anthropocene as a concept. International cooperation is key to developing climate change mitigation policies and resiliency strategies (Helveston et al., 2022; IPCC, 2023; Ng, 2023; Shih, 2022). In the most recent IPCC report, the authors specifically call for international cooperation to support those most vulnerable to the effects of climate change (IPCC, 2023). Collaboration across varying degrees of affluence benefits each party involved, promoting the well-being of regional and global societies and increasing sustainability (Ng, 2023; Steffen and Stafford Smith, 2013). Inclusion of authors from the Global South increases scientific robustness in expanding the capacity of generalizations or perspectives on global solutions or mechanisms (Nakamura et al., 2023).

Altogether, our analyses demonstrate a complicated juxtaposition of the modern spirit and traditional conceptual framework of the Anthropocene with the criteria necessary for its geologic formalization. Whereas geological frameworks require global stratigraphic synchroneity and occurrence, these same criteria are not necessarily extended to academic and popular engagement. To this end, although the Anthropocene has achieved widespread global acceptance in academic disciplines and in popular interest, it remains marred by the same inequities that plague the world more broadly.

5. Conclusions and future directions

The Anthropocene is loosely defined by a broad range of disciplines as the period of time that human activities have changed the mechanisms of the natural environment. More specifically, the term Anthropocene has been used to refer to the modern era, and to societies existing within climate change. The Anthropocene is inherently linked to society, as the concept's genesis was due to humans as a driver of geological, environmental, and ecological change. The two concepts cannot and should not be separated (Hackmann et al., 2014). Even so, the proposed geologic definition of the Anthropocene relates strictly to the global stratigraphic evidence of humans as an agent of geologic change originating in the 1950 s. Social sciences and the humanities have adopted a more holistic definition of the Anthropocene and have used it as such for years. However, even though the physical sciences contribute less to the Anthropocene discussion, the geologic understanding of the Anthropocene does not include the more popular social science or humanity perspectives. Recently, the proposed ratification of the Anthropocene Epoch as an official unit of geologic time was rejected, partially due to lack of breadth (Witze, 2024; Zhong, 2024). The insight and perspectives of social sciences and humanities on the Anthropocene discourse should be included and acknowledged in physical science spaces and publications.

Integrating diverse disciplinary perspectives is a promising and proven way to spur advances in Anthropocene-related research, especially as it pertains to the geological conceptualization of the Epoch (Lundershausen, 2018). To this end, more diverse, interdisciplinary, and transdisciplinary research teams tend to produce more impactful research (Specht and Crowston, 2022; Zhang et al., 2021). For example, interdisciplinary work utilizing social science-based, expert assessment approaches has provided uniquely informative perspectives on the timing and impact of humans on Earth Systems during the Holocene (Sayedi et al., 2024; Stephens et al., 2019). Similarly, integrations of archeological and paleoenvironmental approaches have yielded numerous insights for modern climate and environmental policy

(Kaufman et al., 2018 and examples therein). In addition to programs, funding agencies, or institutions fostering interdisciplinary collaboration, professional organizations can provide a venue for undertaking this work. For example, the Past Global Changes (PAGES) organization hosts the DiverseK working group, which has successfully interfaced environmental and social scientists to gain new understanding of Anthropocene-related problems (Colombaroli et al., 2021; Colombaroli and Larson, 2022).

Akin to these many insights gained by interdisciplinary paleoenvironmental research, future research should aim to further dissect human-environment interactions. Though it is perhaps understated, subscription to the Anthropocene as a concept also implies a worldview; humans can impact and are a part of Earth Systems (Schellnhuber, 1999; Steffen et al., 2020). To this end, Anthropocene research should continue to examine socio-ecological systems in greater detail. For example, recent research has identified that human culture can be detected in the timing of global and continental scale fires (Earl et al., 2015; Pereira et al., 2019, 2015; Vachula et al., 2023), challenging existing paradigms regarding the unidirectionality of human-environmental relationships.

Countries that are most at risk of experiencing adverse effects from climate change during the Anthropocene are also underrepresented in the physical sciences and in decision making spaces (Table 1 and Fig. 3), highlighting the need for further research examining the justice and equity of the Anthropocene. The sustainability of the environment and society depend on merging this understanding of the Earth System with the knowledge and recognition of human justice and inclusivity (Rockström et al., 2023). Although work has begun to account for environmental justice and equity in the conceptual framework of the Anthropocene (e.g., Antadze, 2019; Davis et al., 2019; Gonzalez, 2017; Nixon, 2016), more research and discussion is needed to foster more inclusive engagement with marginalized communities. This need is especially apparent for scientific disciplines, which tend to more resistant to humanistic ideas (Huntington, 2000; Nelson, 2014).

Altogether, our analyses demonstrate that the conceptual and geological frameworks of the Anthropocene share a complex and non-translatable relationship. We urge reconsideration of geologically rigid definitions in the spirit of recognizing holistic recognition of human impacts to the Earth System, while also addressing the gaps in global influence with this pressing concept.

CRediT authorship contribution statement

Richard S Vachula: Writing – review & editing, Writing – original draft, Supervision. **Emma D. Henderson:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have included the data as a supplementary efile.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ancene.2024.100434.

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