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Critical zone science in the Western US—Too much information?

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Exponentially growing publication rates are increasingly problematic for interdisciplinary fields like Critical Zone (CZ) science. How does one "keep up" across different, but related fields with unique hypotheses, field techniques, and models? By surveying CZ academics in the Western US, a region with substantial CZ research, we document the challenge. While conventional knowledge synthesis products-particularly review papers clearly support knowledge transfer, they are static and limited in scope. More informal paths for knowledge transfer, including social networking at conferences and academic mentorship, are useful but are unstructured and problematic for young scientists or others who may not have access to these resources. While new machine-learning tools, including ChatGPT, offer new ways forward for knowledge synthesis, we argue that they do not necessarily solve the problem of information overload in CZ Science. Instead, we argue that what we need is a community driven, machine aided knowledge tool that evolves and connects, but preserves the richness of detail found in peer-reviewed papers. The platform would be designed by CZ scientists, machine-aided and built on the strengths of people-driven synthesis. By involving the scientist in the design of this tool, it will better reflect the practice of CZ science-including hypothesis generation, testing across different time and space scales and in different time periods and locations, and, importantly, the use and evaluation of multiple, often sophisticated methods including fieldwork, remote sensing, and modeling. We seek a platform design that increases the findability and accessibility of current working knowledge while communicating the CZ science practice.

KEYWORDS

synthesis, hydrology, ecology, Critical Zone, review, ChatGPT

Introduction

Critical Zone (CZ) science–the study of processes and interactions extending from the atmosphere to the bedrock–can provide fundamental science information to contribute to the equitable and sustainable management of resources, ecosystem services, and increasingly, climate-related risks. The societal need for synthesizing and advancing CZ research is particularly salient for the Western US, which is facing extensive environmental threats, including but not limited to extreme heat (Tramblay et al., 2020); wildfires (Abatzoglou and Williams, 2016; McLauchlan et al., 2020); severe drought (Cook et al., 2018; Swain et al., 2018; Siirila-Woodburn et al., 2021); widespread habitat loss (Newbold et al., 2020); large scale forest mortality (Hartmann et al., 2022); and pollution of the land, air, and waterways (Artiola et al., 2019; David et al., 2021; Anzalone et al., 2022).

CZ processes have received substantial scientific attention and investment. The Western US provides a good example (Doblas-Miranda et al., 2015). Many of the thematic clusters in the NSF funded Critical Zone Collaborative Network have primary field sites located within the Western US (Dust, Dryland and Dynamics, Geomicrobio, Dynamic Storage) or study processes that are applicable (e.g., the Big Data Cluster). The Collaborative Network also builds on a history of Critical Zone Observatory Networks that included two sites in the Western US. Importantly, understanding of CZ processes continues to evolve not only from work directly funded by NSF CZ initiatives, but also from other scientists and research initiatives including the LTER (Long Term Ecological Research), NEON (National Ecological Observatory Network), US Forest Service Experimental Forest, and university field stations.

These networks, among others, have produced an ever deepening well of knowledge, while also contributing to a staggering and exponentially increasing publication rate in environmental science. Broadly speaking there are roughly ∼2.5 million peer-reviewed journal papers published per year; ∼500,000 in the United States alone (Jinha, 2010; National Science Board National and Science Foundation, 2019). A more CZ specific indicator of the problem scale can be observed by searching for specific topics. For example, using Clarivate Analytics Web of Science to search for "snow or snowpack" just in the Western US produced a total of 16,152 journal papers, with ∼700 papers published per year.

To gauge the magnitude of information overload in CZ science, even within the narrow focus of the Western US, we surveyed environmental scientists and users of environmental science in the Western US. Results from our survey clearly highlight the challenge of synthesizing CZ science (Figure 1). While many academics do skim more than 50 papers a year, most academics only read (start to finish) between 11–50 peer-reviewed papers per year, and non-academics read <10 per year. Given this level of readership, it was unsurprising that respondents considered themselves only "moderately familiar" (academics), or "slightly familiar" (non-academics) with the literature in their respective broad disciplines, such as earth science, life science and social science. Familiarity improved for subdiscipline research among academics with 38% indicating they were "very familiar" and 35% "moderately familiar", while non-academics were primarily "moderately familiar". However, even for relatively narrow subfields, only 35% felt "extremely familiar", and 20% of academics and 27% of non-academics still found the task of finding a methodology or evidence to support a conclusion "somewhat difficult".

Importantly, we can contrast these rates of readership with high publication rates in CZ related topics. For example, using Clarivate Analytics Web of Science to search "fire or wildfire" and the "Western US or California, Oregon, Washington, Arizona, Nevada, Idaho, Utah, Wyoming, Montana, New Mexico, and Colorado" as a topic produces a total of 10,917 peer-reviewed papers, with 2,358 papers published in 2021 alone–more than for the snow example cited earlier. But for either subject, our survey results suggest that those involved in the science enterprise are only reading/viewing a small fraction of papers relative to the publication rate. The publication rate can create problems even for senior scientists well versed in their own literature when attempting to contribute to adjacent fields, or conduct research in a new location. In either case, mistakes can be made, and once published, difficult to remove.

Discussion

Our survey confirms what most of us already know—reading the literature to "keep up", even for well-defined topics that have high societal relevance like CZ science, is difficult if not close to impossible in today's world. While the majority of scientists report being at least moderately familiar with their own sub-field, we argue that there is cause for concern. The 20% of scientists that do not report being familiar with their own subfield, and the substantially lower percentage that are familiar with their general subdiscipline, are likely to be barriers for cross-disciplinary synthesis. Furthermore, if publication rates, even within subfields, are orders of magnitude beyond reported rates of even skimming, much literature is likely lost.

This problem is not new. In the past we have tried to remedy the issue (publication overload) with synthesis products. These include: (1) journals that are devoted to reviewing environmental science (such as Tamm Reviews.); (2) synthesis products—including review papers and databases which are increasingly the focus of funding and synthesis institutes (e.g., the National Center for Ecological Analysis and Synthesis Center, the USGS Powell Center for Analysis and Synthesis, and the National Socio-Environmental Synthesis Center); (3) National Science Foundation programs like Research Coordination Networks; (4) synthesis material from governments and non-governmental organizations (e.g. California's Climate Impact Assessments, IPCC reports); and (5) data provisioning websites that provide data and/or model output relevant to core environmental questions (e.g., Google Earth Engine. Earth Cube, CUASHI's Hydroshare and others).

While these existing initiatives clearly contribute to information synthesis, they are static products and limited in scope. Mistakes can be made if new users stumble upon old or outdated synthesis or if users misapply generalizations to specific locations/circumstances. Newly published papers may diverge from working hypotheses in synthesis papers or may add specificity to general ideas (e.g., quantifying how a general principle, such as how expected earlier snowmelt with climate warming, plays out in a particular location). However, because revisiting synthesis papers rarely happens, this evolution of "current" understanding is easily lost. Synthesis papers and reports also typically focus on particular topics (such as fuel treatment effectiveness), and the linkages to reviews of related topics may not be provided.

As an illustration we can consider the multiple synthesis papers in recent years that are relevant for CZ science of the Western US. Recent reviews highlight hydrologic changes in these semi-arid mountain regions—including declining snowpacks (Siirila-Woodburn et al., 2021), and changes in water availability (Tague et al., 2019), as well as ecological changes—including increasing forest mortality (Anderegg et al., 2015; McDowell et al., 2023) and altered fire regimes (Bowman et al., 2020). While these recent review papers address specific ecologic or

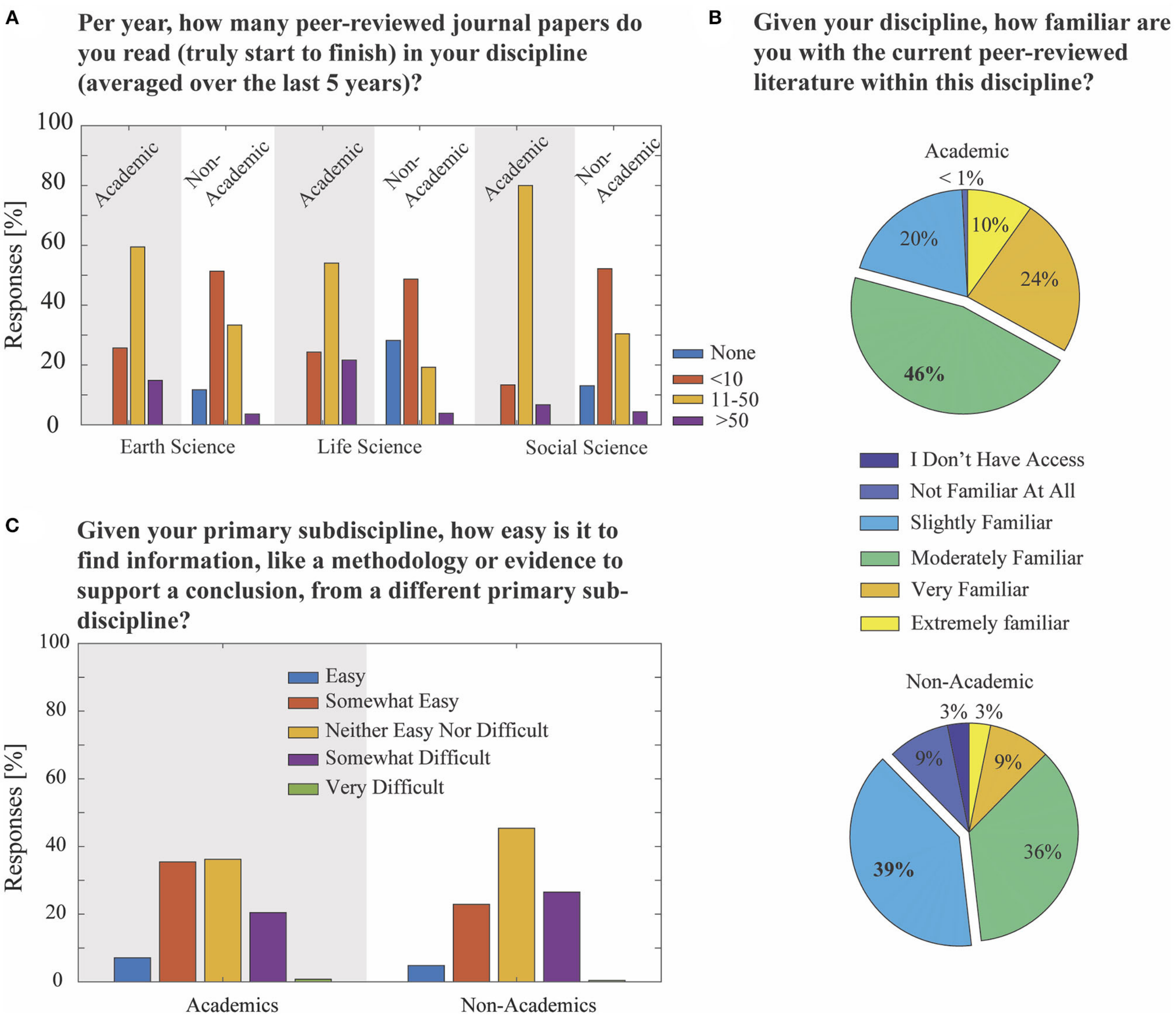

FIGURE 1
Key results from the survey for three questions **(A–C)**.

hydrologic components of climate impacts in these regions, they rarely capture linkages between the subdisciplines and perhaps, most critically, do not incorporate recent work. For example, a highly cited Tamm Review (Hessburg et al., 2016) on the management of mixed severity forests emphasizes how topography influences vulnerability to fire and drought. While the paper acknowledges that "the strength of topographic effects varies by ecoregion, because of unique influences and interactions among geology, geomorphology, and prevailing wind and weather patterns," the citational support was limited. Today there is now a broader literature that explores and quantifies these topographic patterns at different scales. More recent papers, for example, demonstrate the importance of bedrock heterogeneity as a control on forest drought mortality (Callahan et al., 2022); and advances in snow remote sensing/modeling have better quantified Sierra Nevada precipitation patterns, notably showing that precipitation generally declines at high elevations (Huning and Margulis, 2018). This example highlights the limitation of static review papers. Further, the diversity of synthesis products themselves can still be overwhelming, contributing further to the information overload.

If human generated synthesis products cannot save us, what about Artificial intelligence (AI)? Improved automated searches, and/or distilled information that uses machine learning (i.e., web-based products like: iris.ai, Semantic Scholar, Connected Papers, Open Knowledge Maps, and Local Citation Network) can help to search for and find information (Matthews, 2021). Nonetheless, extracting meaningful searches of environmental publications around specific topics remains challenging (Romanelli et al., 2021). Further, **finding literature does not necessarily lead to understanding**, particularly if searches yield hundreds of papers. Focusing on highly cited papers may also be problematic, given that the reason for high citation rates may not align with the goal of understanding (Romanelli et al., 2021) and can lead to bias (Perc, 2014). Similarly, automated mapping of domain knowledge—where AI algorithms are used to cluster papers around semantic terms—can highlight topical areas and show how these topics evolve but they do not necessarily provide a synthesis of underlying ideas (Börner and Polley, 2014; Lafia et al., 2021).

The emergence of ChatGPT and other large language models (LLMs) extend past AI-driven synthesis and could be used to improve "Literature based discovery", where an AI assistant, or copilot, helps a scientist discover new conclusions from existing literature and points to future collaborators. However, to define the evolving frontiers and hypotheses of an interdisciplinary science (i.e., for a science like CZ) the effectiveness of LLMs will depend on expert-driven training. LLMs are a synthesis of both our language and ideas–past and present–and this design strength (the ability to utilize vast sources of information) is also their greatest weakness when applied to the discovery of science frontiers.

Expert intervention is needed. Without this, ChatGPT and other LLMs will have limited quality control such that unsupervised synthesis can produce ideas and citations that are either wrong or cease to exist. In addition, without guidance, LLMs may reinforce existing issues of over-reliance on highly cited (e.g., common) papers and their ideas (Lund et al., 2023). Today, the use of LLMs for science remains a challenge because extracting an understanding of current frontiers relies on effective prompt engineering, which involves knowing how to ask good questions of LLMs (as discussed by Zhu et al., 2023), and this skill is likely inaccessible for non-experts. ChatGPT style synthesis, while useful for those seeking general knowledge, does not easily lend itself to the more nuanced, detailed understanding that guides disciplinary research. While some of these limitations may be overcome, a more scientifically useful synthesis will likely need experts to guide how scientific literature is searched, structured, and queried.

A way forward—Reconfigure the building blocks

Classic narrative review papers do more than find literature—they synthesize the ideas embedded within those papers, and highlight convergence and divergence around core hypotheses (Polonioli, 2020). Synthesis papers also evaluate the techniques used in both observational data collection, and/or in generating model output. These narratives are typically written by experts who use that expertise to place papers into conceptual frameworks that guide understanding and identify gaps in knowledge. As noted above, however, these human driven synthesis papers are static, often narrow in focus, and only partially survey a growing literature.

Rather than approaching a solution from an exclusive binary choice–maybe a better path forward is a blend of strengths–**a human driven, machine aided knowledge tool that evolves and connects, but preserves the richness of detail found in individual peer-reviewed papers.** This online platform would combine: (1) the strengths of human-driven science review and synthesis; (2) state-of-the-art visualization; (3) machine driven techniques for searching; (4) digital tools to support continual updating by scientists; (5) work in tandem with today's journals who provide quality control through peer-review and (6) follow FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016) that have been widely used in the design of shared data repositories.

To build such a platform would require a collaborative process, **in which the scientist is involved in the product feedback loop at every step** to ensure that machine's find, process, and present information in ways that are consistent with how science itself evolves. We argue that if the process is initiated and led by scientists, the resulting product will be a better fit for our needs and reflect core features of CZ science practice that we use to both mentor new CZ scientists (Fouad and Santana, 2017) and to find and evolve the frontiers of knowledge.

What are these core features? Central to all science is the formulation of hypothesis and testing (Pfister and Kirchner, 2017). Understanding of CZ science, however, requires combining multiple hypotheses from different disciplines and investigating their interaction. Further, what is most challenging about CZ science is that most hypotheses require postulation, testing, and refinement for different space and time scales and at different locations and periods within those scales. Identifying and explaining location specific exceptions to general theories is a key part of the evolution of CZ science [e.g. see examples from CZ architecture (Riebe et al., 2017), hydrology (Wlostowski et al., 2021), ecosystem function (Hoylman et al., 2019) and snow (Siirila-Woodburn et al., 2021)]. Furthermore, CZ science employs a wide diversity of sophisticated methods that range from field based measures, to remote sensing and modeling. Understanding the strengths and limitations and employing best-practices in their applications is central to CZ-science practice. As a result, a core component of CZ research focuses on evaluating these methods and revealing implications of limitations in their application (Brantley et al., 2017).

We seek an online platform design that preserves and communicates these features of CZ science while increasing the findability and accessibility of current working knowledge/hypotheses. The proposed platform would treat peer-reviewed publications as "data" (i.e., Lafia et al., 2021), but utilize a front end of interconnected "pages" to provide the context and access to "the data" in ways that are consistent with CZ science practice. These pages would include: (1) conceptual diagrams; (2) current working hypothesis and counter hypothesis; (3) examples of how these hypotheses are realized (or not) across time and space scales (and for specific periods and locations); and (4) overviews of methods and best practices for their application–all of which would be linked with peer-reviewed papers. We emphasize that such a platform could be designed and built with existing technology; essentially, it would function as a web application (Börner et al., 2005). Therefore, it could be hosted on existing cloud computing services (i.e., DigitalOcean), and the backend could be designed to leverage existing AI-driven systems, which would be trained by experts to aid in search and updating procedures (Coon et al., 2016; Ibáñez and Delgado-Kloos, 2018). The front-end "pages" could be structured by experts but allowed to evolve with ChatGPT style user adaptation.

While the design of this new platform is by no means simple, arguably the more complex and important challenge is to design an effective plan for the platform's governance. We want a tool that engages and supports the collaboration that is essential for moving CZ forward (Arora et al., 2023). The goal of the tool would be to address barriers to entry into CZ science communities, particularly for disadvantaged scientists, associated with gaining access to what defines "the cutting edge" in these research domains (Thakore et al., 2014; Nocco et al., 2021). To do this we would need strategies to fully engage the CZ research community, including experts, early-career scientists, and scientists with a diverse set of backgrounds and strengths. Strategies for shared governance can take advantage of what has been learned by shared development of knowledge platforms in general (Manesh et al., 2020) and more recently around how to incorporate natural language processing like ChatGPT into knowledge platform design (Hu et al., 2023). Contributions would need to adhere to a strict set of rules for both governing and updating. For updating, these rules would require careful consideration on how best to leverage the existing peer review process to maintain credibility while at the same time creating a flexible, dynamic, and FAIR system. Much can be learned from how shared knowledge projects like Wikipedia have evolved, both in terms of governance and incentives for engagement (Bruckman, 2022). The main challenge is a "human-centered" one, and how to harness the CZ community. The more users, and the larger the contributing community, the better the product.

Along with shared governance comes the challenge of funding. A successful platform would need support by funding agencies. The community building would need to leverage existing support for science synthesis and the practical knowledge that synthesis organizations (such as the National Center for Ecological Analysis and Synthesis (NCEAS), or the USGS Powell Center) have gained related to consensus building. New funding sources, including potential partnerships with AI-provisioning companies, would need to be carefully explored.

Publication overload in environmental science in general, and within CZ science, necessitates new ways to efficiently find current (and past) hypotheses from interconnected disciplines and their realization at relevant scales and locations along with practical understanding of current methods (where they work and where they don't). To build such a platform requires disparate scientific communities to work together including scientists, visualization experts, database specialists, ontologists, and AI and machine learning experts. This collaborative process, in which the scientist (i.e., the CZ scientist) is involved at every step, is critical to building an effective solution for information overload. We argue that if the process is initiated and led by scientists, the resulting product will better fit the needs of the CZ (and other environmental science communities). Waiting for a private sector solution, such as a "better" Google Scholar or more detailed ChatGPT, will not necessarily ensure that the strengths of human-driven science are maintained. The explosion of new scientific information combined with critical needs for "the state of the science" in an era of unprecedented environmental change demands we do something. The need is here, we have the tools, and the timing is right for a radical transformation of how we present and summarize our scientific knowledge—but are we bold enough to take the leap?

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by University of California Santa Barbara Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

All authors participated equally in all aspects of this manuscript, including survey design and analysis, and conceptualization and writing of the manuscript. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2023.1226612/full#supplementary-material

SUPPLEMENTARY MATERIAL

Figure 1; note survey questions have been included in the Supplementary material. In March 2021, the survey was distributed across academia, government and the private sector. The survey was built using Qualtrics and distributed via email to environmental science departments within the Western US, national parks in the Western US, academic social networks (e.g., the Organization of Biological Field Stations, and Environmental and Resource Economics Network), federal intuitions and labs (e.g., NASA JPL, USGS, USFS, NCAR/UCAR, National Snow and Ice Data Center), state institutions (e.g., the California Air Resources Board, and California's Department of Water Resources), city institutions (e.g., Seattle Public Utilities, and Casitas Municipal Water District), nonprofits (e.g., California Council on Science & Technology, and Public Policy Institute of California), and private companies (e.g., Vibrant Planet, and Airborne Snow Observatories Inc.). Of the 443 responses, 220, 177, and 46 responders identified as being in the Earth, Life, and Social science disciplines, respectively. Academics represented 34% of the respondents, while 66% were non-academics (i.e., from public and private institutions).

References

Abatzoglou, J. T., and Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proc. Nat. Acad. Sci.* 113, 11770–11775. doi: 10.1073/pnas.1607171113

Anderegg, W. R. L., Hicke, J. A., Fisher, R. A., Allen, C. D., Aukema, J., Bentz, B., et al. (2015). Tree mortality from drought, insects, and their interactions in a changing climate. *New Phytol.* 208, 674–683. doi: 10.1111/nph.13477

Anzalone, S. E., Fuller, N. W., Hartz, K. E. H., Fulton, C. A., Whitledge, G. W., Magnuson, J. T., et al. (2022). Pesticide residues in juvenile Chinook salmon and prey items of the Sacramento River watershed, California – a comparison of riverine and floodplain habitats. *Environ. Pollut.* 303, 119102. doi: 10.1016/j.envpol.2022.119102

Arora, B., Kuppel, S., Wellen, C., Oswald, C., Groh, J., Payandi-Rolland, D., et al. (2023). Building cross-site and cross-network collaborations in critical zone science. *J. Hydrol.* 618, 129248. doi: 10.1016/j.jhydrol.2023.129248

Artiola, J. F., Walworth, J. L., Musil, S. A., and Crimmins, M. A. (2019). Soil and Land Pollution. *Environ. Pollut. Sci.* 14, 219–235. doi: 10.1016/B978-0-12-814719-1.00014-8

Börner, K., Chen, C., and Boyack, K. W. (2005). Visualizing knowledge domains. *Ann. Rev. Inf. Sci. Technol.* 37, 179–255. doi: 10.1002/aris.1440370106

Börner, K., and Polley, D. E. (2014). *Visual Insights: a Practical Guide to Making Sense of Data*. Cambridge, Ma: The MIT Press.

Bowman, D. M. J. S., Kolden, C. A., Abatzoglou, J. T., and Johnston, F. (2020). Vegetation fires in the anthropocene. *Nat. Rev. Earth Environ.* 1, 500–515. doi: 10.1038/s43017-020-0085-3

Brantley, S. L., McDowell, W. H., Dietrich, W. E., White, T. S., Kumar, P., Anderson, S. P., et al. (2017). Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. *Earth Surf. Dynam.* 5, 841–860. doi: 10.5194/esurf-5-841-2017

Bruckman, A. S. (2022). *Should You Believe Wikipedia?: Online Communities and the Construction of Knowledge*. Cambridge: Cambridge University Press.

Callahan, R. P., Riebe, C. S., Sklar, L. S., Pasquet, S., Ferrier, L. L., Hahm, W. J., et al. (2022). Forest vulnerability to drought controlled by bedrock composition. *Nat. Geosci.* 15, 714–719. doi: 10.1038/s41561-022-01012-2

Cook, B. I., Mankin, J. S., and Anchukaitis, K. J. (2018). Climate change and drought: from past to future. *Curr. Clim. Chan. Rep.* 4, 164–179. doi: 10.1007/s40641-018-0093-2

Coon, E. T., David Moulton, J., and Painter, S. L. (2016). Managing complexity in simulations of land surface and near-surface processes. *Environ. Model. Softw.* 78, 134–149. doi: 10.1016/j.envsoft.2015.12.017

David, L. M., Ravishankara, A. R., Brey, S. J., Fischer, E. V., Volckens, J., and Kreidenweis, S. (2021). Could the exception become the rule? "Uncontrollable" air pollution events in the U.S. due to wildland fires. *Environ. Res. Let.* 16:034029. doi: 10.1088/1748-9326/abe1f3

Doblas-Miranda, E., Martínez-Vilalta, J., Lloret, F., and Álvarez, A., Ávila, A., Bonet, F. J., et al. (2015). Reassessing global change research priorities in mediterranean terrestrial ecosystems: how far have we come and where do we go from here?: Global change research in MTEs. *Glob. Ecol. Biogeo.* 24, 25–43. doi: 10.1111/geb.12224

Fouad, N. A., and Santana, M. C. (2017). SCCT and underrepresented populations in STEM fields: moving the needle. *J. Career Asses.* 25, 24–39. doi: 10.1177/1069072716658324

Hartmann, H., Bastos, A., Das, A. J., Esquivel-Muelbert, A., Hammond, W. M., Martínez-Vilalta, J., et al. (2022). Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. *Annu. Rev. Plant Biol.* 73, 673–702. doi: 10.1146/annurev-arplant-102820-012804

Hessburg, P. F., Spies, T. A., Perry, D. A., Skinner, C. N., Taylor, A. H., Brown, P. M., et al. (2016). Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and Northern California. *For. Ecol. Manage.* 366, 221–250. doi: 10.1016/j.foreco.2016.01.034

Hoylman, Z. H., Jencso, K. G., Hu, J., Holden, Z. A., Allred, B., Dobrowski, S., et al. (2019). The topographic signature of ecosystem climate sensitivity in the western United States. *Geophy. Res. Let.* 46, 14508–14520. doi: 10.1029/2019GL085546

Hu, X., Tian, Y., Nagato, K., Nakao, M., and Liu, A. (2023). Opportunities and challenges of ChatGPT for design knowledge management. *arXiv. [preprint]. arXiv:2304.02796*. doi: 10.48550/arXiv.2304.02796

Huning, L. S., and Margulis, S. A. (2018). Investigating the variability of high-elevation seasonal orographic snowfall enhancement and its drivers across Sierra Nevada, California. *J. Hydrometeorol.* 19, 47–67. doi: 10.1175/JHM-D-16-0254.1

Ibáñez, M.-B., and Delgado-Kloos, C. (2018). Augmented reality for STEM learning: A systematic review. *Comp. Educ.* 123, 109–123. doi: 10.1016/j.compedu.2018.05.002

Jinha, A. E. (2010). 50 million: an estimate of the number of scholarly articles in existence. *Learn. Publ.* 23, 258–263. doi: 10.1087/20100308

Lafia, S., Kuhn, W., Caylor, K., and Hemphill, L. (2021). Mapping research topics at multiple levels of detail. *Patterns* 2, 100210. doi: 10.1016/j.patter.2021.100210

Lund, B. D., Wang, T., Mannuru, N. R., Nie, B., Shimray, S., and Wang, Z. (2023). ChatGPT and a new academic reality: artificial Intelligence-written research papers and the ethics of the large language models in scholarly publishing. *J. Assoc. Inform. Sci. Technol.* 74, 57–81. doi: 10.1002/asi.24750

Manesh, M. F., Pellegrini, M. M., Marzi, G., and Dabic, M. (2020). Knowledge management in the fourth industrial revolution: Mapping the literature and scoping future avenues. *IEEE Trans. Eng. Manag.* 68, 289–300. doi: 10.1109/TEM.2019.2963489

Matthews, D. (2021). Drowning in the literature? These smart software tools can help. *Nature* 597, 141–142. doi: 10.1038/d41586-021-02346-4

McDowell, N. G., Anderson-Teixeira, K., Biederman, J. A., Breshears, D. D., Fang, Y., Fernandez-de-Una, L., et al. (2023). Ecohydrological decoupling under changing disturbances and climate. *One Earth* 6, 251–266. doi: 10.1016/j.oneear.2023.02.007

McLauchlan, K. K., Higuera, P. E., Miesel, J., Rogers, B. M., Schweitzer, J., Shuman, J. K., et al. (2020). Fire as a fundamental ecological process: research advances and frontiers. *J. Ecol.* 108, 2047–2069. doi: 10.1111/1365-2745.13403

National Science Board and National Science Foundation (2019). *Publications Output: U.S. Trends and International Comparisons*. Alexandria, VA: National Science Board and National Science Foundation.

Newbold, T., Oppenheimer, P., Etard, A., and Williams, J. J. (2020). Tropical and Mediterranean biodiversity is disproportionately sensitive to land-use and climate change. *Nat. Ecol. Evol.* 4, 1630–1638. doi: 10.1038/s41559-020-01303-0

Nocco, M. A., McGill, B. M., MacKenzie, C. M., Tonietto, R. K., Dudney, J., Bletz, M. C., et al. (2021). Mentorship, equity, and research productivity: lessons from a pandemic. *Biol. Conserv.* 255, 108966. doi: 10.1016/j.biocon.2021.108966

Perc, M. (2014). The Matthew effect in empirical data. *J. R. Soc. Int.* 11, 20140378. doi: 10.1098/rsif.2014.0378

Pfister, L., and Kirchner, J. W. (2017). Debates—Hypothesis testing in hydrology: theory and practice. *Water Resour. Res.* 53, 1792–1798. doi: 10.1002/2016WR020116

Polonioli, A. (2020). In search of better science: on the epistemic costs of systematic reviews and the need for a pluralistic stance to literature search. *Scientometrics* 122, 1267–1274. doi: 10.1007/s11192-019-03333-3

Riebe, C. S., Hahm, W. J., and Brantley, S. L. (2017). Controls on deep critical zone architecture: a historical review and four testable hypotheses. *Earth Surf. Proc. Landforms* 42, 128–156. doi: 10.1002/esp.4052

Romanelli, J. P., Gonçalves, M. C. P., Pestana, L. F., d, Soares, J. A. H., Boschi, R. S., and Andrade, D. F. (2021). Four challenges when conducting bibliometric reviews and how to deal with them. *Environ. Sci. Pollut. Res.* 28, 60448–60458. doi: 10.1007/s11356-021-16420-x

Siirila-Woodburn, E. R., Rhoades, A. M., Hatchett, B. J., Huning, L. S., Szinai, J., Tague, C., et al. (2021). A low-to-no snow future and its impacts on water resources in the western United States. *Nat. Rev. Earth Environ.* 2, 800–819. doi: 10.1038/s43017-021-00219-y

Swain, D., Langenbrunner, B., Neelin, J. D., and Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nat. Climate Change*, 8, 427. doi: 10.1038/s41558-018-0140-y

Tague, C. L., Moritz, M., and Hanan, E. (2019). The changing water cycle: the eco-hydrologic impacts of forest density reduction in Mediterranean (seasonally dry) regions. *WIREs Water* 6, e1350. doi: 10.1002/wat2.1350

Thakore, B. K., Naffziger-Hirsch, M. E., Richardson, J. L., Williams, S. N., and Jr, R. M. (2014). The Academy for Future Science Faculty: randomized controlled trial of theory-driven coaching to shape development and diversity of early-career scientists. *BMC Med. Educ.* 14, 160. doi: 10.1186/1472-6920-14-160

Tramblay, Y., Koutroulis, A., Samaniego, L., Vicente-Serrano, S. M., Volaire, F., Boone, A., et al. (2020). Challenges for drought assessment in the Mediterranean region under future climate scenarios. *Earth-Sci. Rev.* 210, 103348. doi: 10.1016/j.earscirev.2020.103348

Wilkinson, M. D., Dumontier, M., Aalbersberg, I. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* 3, 1–9. doi: 10.1038/sdata.2016.18

Wlostowski, A. N., Molotch, N., Anderson, S. P., Brantley, S. L., Chorover, J., Dralle, D., et al. (2021). Signatures of hydrologic function across the critical zone observatory network. Water Resources Research, 57, e2019WR026635. doi: 10.1029/2019WR026635

Zhu, J.-J., Jiang, J., Yang, M., and Ren, Z. J. (2023). ChatGPT and environmental research. *Environ. Sci. Technol.* acs.est.3c01818. doi: 10.1021/acs.est.3c01818