Integrated, Coordinated, Open, and Networked (ICON) Science to Advance the Geosciences: Introduction and Synthesis of a Special Collection of Commentary Articles

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Key Points:

- All 19 represented AGU sections agree that ICON science principles are key to producing stronger, more robust, and more equitable science.
- The benefits of all ICON principles outweigh associated costs, but risks need to be understood and mitigated.
- ICON principles are not static; details of their use are context dependent, emphasizing a need for resources to guide ICON implementation.

Abstract

The sciences struggle with poor integration across disciplines, the absence of coordination within and across data generation and modeling activities, scarce or disconnected open data, and weaknesses of networks to engage diverse stakeholders within and beyond the scientific community. The American Geophysical Union (AGU) is divided into 25 sections intended to encompass the breadth of the geosciences. Here, we introduce a special collection of commentary articles spanning 19 AGU sections on the challenges and opportunities associated with the use of ICON science principles. These principles focus on research intentionally designed to be Integrated, Coordinated, Open, and Networked (ICON) with the goal of maximizing mutual benefit (among stakeholders) and cross-system transferability of science outcomes. This article summarizes the ICON principles; discusses the crowdsourced approach to creating the collection; and explores insights from across the articles. There were multiple common themes among the commentary articles, including the broad agreement that the benefits of using ICON principles outweigh the costs, but that using ICON principles has important risks that need to be understood and mitigated. It was also clear that the ICON principles are not monolithic or static, but should instead be considered a heuristic tool that can and should be modified to meet changing needs. As a whole, the collection is intended as a resource for scientists pursuing ICON science and represents an important inflection point in which the geosciences community has come together around ICON principles as a unified approach for improving how science is done across the geosciences and beyond.

Plain Language Summary

Researchers often ignore that the way that scientific research is designed and carried out influences who and what benefits from the research outcomes. The ICON principles are designed to help scientists overcome this limitation. These principles are based on intentionally designing research to Integrate disciplines, Coordinate use of consistent methods, Openly share ideas/data, and Network with diverse stakeholders to understand needs and distribute efforts towards mutual benefit. The relevance of these principles and how to best use them across a spectrum of research is, however, unknown. A collection of commentary articles was crowdsourced from across the geosciences community to fill this gap. We report on the process of bringing the collection together and summarize themes that emerged across 163 researchers. The articles are clear that the geosciences community sees significant value in using ICON principles, while acknowledging there are risks as well. We also observed that ICON principles should be considered a flexible tool to meet diverse needs. ICON principles represent a unified approach that can be embraced by all the geosciences to improve the foundations of how research is designed and implemented with the aim of maximizing the benefit of research efforts within and beyond the research team.

1 Introduction

This article serves as the introduction to a special collection of commentary articles titled “The Power of Many: Opportunities and Challenges of Integrated, Coordinated, Open, and Networked (ICON) Science to Advance Geosciences”. The ICON Collection is intended to be a resource for researchers across disciplines who are interested in intentionally doing science following a framework referred to as the ICON principles. To maximize its applicability across geoscience disciplines, the Collection was designed to include one article from each of the 25 American Geophysical Union (AGU) section disciplines, and to date, 19 sections have articles prepared for submission to the Collection. This article (1) provides an overview of the ICON principles; (2) discusses the ICON-enabled approach to creating the crowdsourced collection; (3) summarizes insights from across the articles and the authors' experiences; and (4) explores lessons learned and next steps for ICON science.

1.1 What is ICON?

ICON science is an approach to designing and carrying out research activities that has existed in many forms throughout scientific disciplines but coalesced into a framework in a 2019 U.S. Department of Energy (DOE) Biological and Environmental Research (BER) workshop report (U.S. DOE, 2019). Goldman et al., (2021) advertised involvement in the ICON Collection and provided definitions for each ICON principle. Here, based on the commentary articles, we have slightly modified the definitions in an attempt to reflect geoscience-wide perspective on what ICON science is meant to be:

1. **Integrates** processes across traditional disciplines (i.e., physical, chemical, and biological) and across spatial and/or temporal scales;
2. **Coordinates** use of consistent protocols across systems to generate data that is interoperable across systems and researchers, often with a focus on data types needed to inform, develop, and improve models;
3. **Openly** exchanges ideas, data, software, and models throughout the research lifecycle that are findable, accessible, interoperable, and reusable (FAIR) such that all researchers are enabled to contribute and leverage resources; and
4. **Networks** efforts, whereby data generation, sample collection, and/or other phases of the research lifecycle are done with and for the scientific and/or stakeholder community, creating research that is mutually beneficial while providing resources (e.g., data, models, sensors, results) to contributors that otherwise would be difficult or impossible for them to access.

These definitions are not static. The ICON Collection was approached with an awareness that the different AGU sections would have a spectrum of perspectives on what each piece of ICON meant within their discipline. Each assembly of writing teams elaborated upon definitions and expanded them as needed. Each ICON principle is described in more detail in the following paragraphs, including examples from articles within the collection, recognizing that these definitions may differ from others.

1.1.1 Integrated

There was agreement across all of the articles on the importance of integration to scientific impact and advancement. Some of the AGU sections even have integration across disciplines built into their names (e.g., Biogeosciences). However, the complexity of integration can make it challenging to achieve. In the ICON Collection's Natural Hazards article, Sharma et al., (2021) describe that addressing the need to assess multihazard multisector risk requires the "integrated assessment of hazard probabilities, the exposure of people and assets, and the vulnerability or susceptibility to consequent damage." Because multihazard risks are dependent on many factors such as climate, demographics, and socioeconomic conditions, the integrated understanding of these risk drivers is essential to a comprehensive view of natural hazard systems (Sharma et al., 2021).

1.1.2 Coordinated

A common driver behind geoscience research questions is to discover explanations and causality to phenomena regardless of location and time. To accomplish this, data and findings must be comparable across space and time to allow hypotheses to be investigated across diverse settings and scales. The 'Coordinated' principle addresses the need to share protocols and methods that allow for improved quality and utility of the data generated resulting from consistency in its collection. In the ICON Collection's Cryosphere Sciences article, Brügger et al., (2021) highlight that different ice core laboratories may establish chronologies or proxies in ice cores using different methods, leading to challenges comparing within and across ice core records. The importance of the 'Coordination' principle extends beyond physical sample collection. In the Earth and Space Science Informatics article, Hills et al., (2021) describe the importance of coordinated efforts "to implement standards for effective interdisciplinary data discovery and exchange…", yet point out that there are limitations in data reuse and discovery due to the lack of consistent and transparent protocols, for example in data and code production, and processing methods across interdisciplinary teams.

1.1.3 Open

The 'Open' principle of ICON refers most closely to the "Open Science by Design" framework laid out by the National Academies of Science, Engineering, and Math and elaborated upon in the "Open Watershed Science by Design" report from the U.S. Department of Energy. Open access in data repositories and research publications is one component, but the 'Open' principle encompasses achieving openness in the whole lifecycle of research: provocation, ideation, knowledge generation, validation, dissemination, and preservation (National Academies of Sciences, Engineering, and Medicine, 2018; U.S. DOE, 2019). The 'Open' principle of ICON is also intentionally defined to include the FAIR (findable, accessible, interoperable, reusable) data principles (Wilkinson et al., 2016). ICON is often used interchangeably with ICON-FAIR to make this more explicit, because as a general concept openness does not require being FAIR and vice versa, as highlighted in the ICON Collection's Earth and Space Science Informatics article (Hills et al., 2021). Some barriers to achieving the 'Open' principle are consistent across fields and some are discipline-specific. In the Paleoclimatology and Paleoceanography article, (Belem et al., In prep.) describe one of the open science challenges as accessing "dark data," data collected before online and digitized data collection tools. Another challenge described by Belem and colleagues is in knowing where to look for data that a researcher needs because of the lack of a centralized and organized catalog of the databases and their contents. In the Biogeosciences article, Dwivedi et al., (2021) also describe that openness measured in publications does not translate to openness for the average citizen anywhere in the world. They call for a need to incentivize the dissemination of findings beyond the professional scientific community (Dwivedi et al., 2021).

1.1.4 Networked

Most science ultimately is pursued as a benefit to society. 'Networked' goes beyond the casual, conference-style networking that happens, before, during, and after the workday, and instead focuses on the benefits of mutualism in the sciences. Mutually beneficial research can take the form of working with collaborators in such a way that their needs or interests are met, in addition to an individual or study's original research needs or questions; However, mutualism can and often should go beyond the individual researchers involved so that the wider community, including stakeholders, land stewards, and beyond, are considered. A key point underpinning the ‘Networked’ principle is that designing research to be mutually beneficial for people involved and/or impacted is inherently linked to diversity, equity, inclusion, and, in the geosciences, often to environmental justice. One component of this is considering current and historical disenfranchisement that restricts certain groups from participating in the economic marketplace, scientific forums, governance, and other spaces that ultimately affect decision making. In part, this requests that researchers ask themselves questions before proceeding with a study design. In the Hydrology article, (Acharya et al., 2021) provide a specific example binned into four categories: “(1) ‘Who is doing the hydrology?’ How will marginalized communities be involved? Will they have the same ‘power and privileges’ as non-marginalized communities? Who will own the scholarly outputs (e.g., data, grant proposals)?; (2) ‘Who uses the water?’ If marginalized communities are main water users, will they (or their communities) be able to sustain or use the hydrology knowledge research/work effectively (e.g., beyond the end of a project)?; (3)’Who benefits from this activity?’ Will marginalized communities get appropriate and meaningful attribution for their contribution? Will resources and infrastructure be available/sustained to marginalized communities after a project ends?; and (4) ‘Why?’ What is the purpose of this work and how will marginalized communities benefit and be supported?” The same article provides an example of work being done to strengthen the access and role of indigenous peoples in water research affecting their communities (Acharya et al., 2021). In the GeoHealth article, Barnard et al., (In prep.) highlight the importance of valuing the expertise of local leadership and communities in an effort to strengthen scientific arguments. In the Biogeosciences article, Dwivedi et al., (2021) suggest that a key challenge to networked efforts are the international cultural differences and resource variances that can cause the contributions of researchers in low-income and under-resourced countries to be undervalued or diminished. Ultimately, this disconnect can lead to a lack of understanding of historical scientific content, and subsequently misinterpretation of results and improper conclusions. The ‘Networked’ principle is intended to elevate equity by identifying where sciences can be built on the foundation of mutual benefit through strategic scientific resourcing. Many of the articles in the ICON Collection have identified that the ‘Networked’ principle is anticipated to have the greatest benefit to the sustainability of the respective fields.

1.2 Goal of the Special Collection

The ICON Collection was created to be a resource for researchers aiming to advance the geosciences through intentionally doing science following the ICON principles. Using ICON principles can be challenging due to the need for more a priori planning, logistical coordination, and stakeholder engagement, relative to many (but not all) traditional ways of doing science. How ICON principles are used also varies across research settings due to variation in numerous practical factors such as discipline-specific technical considerations, available funding and instrumentation, stakeholder needs, and science objectives. An additional challenge is that most scientists are not trained in how to intentionally develop and implement research projects that fully embody ICON principles. These challenges and lack of training are roadblocks to broad use of ICON principles. A primary goal of the collection is to bring together diverse perspectives on challenges, solutions, and opportunities associated with ICON science to reduce roadblocks and enable broader use of ICON principles across the geosciences and beyond.

2 Approach

2.1 Overview of structure

The ICON Collection was meant to span all AGU sections using a crowdsourced collaborative writing approach. Each AGU section was allotted one commentary article comprising contributions from up to three independent writing teams. Each writing team was based on a theme, and the themes were crowdsourced from the writers to allow the community to guide specific directions of the manuscripts. This was done to bring together new teams and maximize opportunities for the global geosciences community. The associated process is detailed below. Through this process we observed the emergence of common themes as well as discipline-specific perspectives across the contributed manuscripts, which are also discussed below.

2.2 Conceptualization

The approach used to create the ICON Collection was intentionally designed to follow ICON principles and provided valuable examples of opportunities and challenges that result from implementing ICON. Below we describe the approach used to create the Collection with the intention of helping to facilitate other crowdsourced paper collections in the future. A Town Hall led by members of the ICON Collection leadership team at the AGU 2019 Fall Meeting was a launch point for the Collection. The Town Hall, "Coordinated Open Science by Design to Transform the Geosciences," aimed to catalyze a special collection by bringing together geoscientists across fields and engaging in active discussions about examples, opportunities, and challenges of ICON science. We invited several panelists that spanned disciplines to provide a base of perspectives and discussions inherently integrated across disciplines. Because only AGU Fall Meeting attendees could participate, using the Fall Meeting also meant that some people were excluded from the opportunity. We accepted the limitations of the Town Hall, because the actual engagement in creating the Collection articles would be open. This exemplifies an easy pitfall of trying to pursue open and equitable science throughout the research lifecycle; many scientific opportunities are not fully open, and it is critical to consider who is being excluded and why. As part of small group activities, Town Hall attendees discussed and wrote responses to the same list of questions, including whether they were interested in contributing to a special collection. This coordinated approach allowed us to compile a spreadsheet of ICON challenges and opportunities across disciplines that helped guide early development of the Collection structure. Soon after the Town Hall, we worked with AGU journal staff to identify a target journal and develop a special collection proposal.

2.3 Creation of infrastructure

Members of the Collection leadership team held a workshop for the people who had attended the Town Hall to gather feedback on the proposed vision and structure of the Collection. We created a series of foundational documents informed by the workshop discussions that defined the ICON Collection approach, author guidelines, team norms, writing contribution guidelines, and roles and responsibilities. We expanded the Collection leadership team to five people to span a greater range of geoscience fields, and the new team iterated on the foundational documents to clarify the vision and approach and integrate ideas from the new leadership team members. The foundational documents played a critical role in creating coordination for the Collection. For the published commentary articles themselves, the foundational documents set instructions that allowed for flexibility while assuring the published content would follow a consistent framework to form a cohesive resource. For interpersonal dynamics of the writing teams, the foundational documents set guidelines and expectations with the intent of minimizing conflict, maximizing open communication, and creating an expectation of mutual respect.

2.4 Advertisement and recruiting

The leadership team made the completed foundational documents public and began a multi-month open advertising campaign for people to sign up to get involved in the Collection. The advertising campaign included an Eos Vox (Goldman et al., 2021), a series of Twitter posts, discipline-specific mailing lists, announcements during meeting presentations, emails to colleagues, cold-emails to organizational leadership, direct engagement with AGU section leadership, and posting to the AGU Connect message boards and associated email newsletters. We particularly reached out to affinity groups like Geolatinas, 500 Women Scientists, Black in Geoscience, and ADVANCEGeo who helped distribute the information in their social media platforms and with their members. We encouraged people to spread the word to their colleagues, collaborators, followers, and beyond. During the advertising campaign, we worked with AGU to present the Collection at a monthly meeting for AGU Section Presidents to better understand how we could engage members across each of the 25 AGU sections. When signing up to get involved in the Collection, people could select interest in being a writer in the Collection, a “section champion,” or both. The section champion was a facilitator role so that each article would have one or two people that communicated directly with the leadership team and understood the Collection structure and expectations. The champions were encouraged to reach out to their networks and colleagues during the advertising period. To equip the champions for their role and gather feedback, we held a workshop with the champions that was also recorded and posted to YouTube (https://tinyurl.com/SCworkshopICON). The workshop also provided a valuable opportunity to start building a sense of community among those involved in the Collection.

After implementing the strategies described above to recruit people for the Collection, the leadership team faced the challenge of highly variable numbers of sign-ups across the 25 AGU sections. We reached out to the AGU Section Presidents of the sections that had few or no sign-ups. This approach increased the number of participants in some but not all the sections. We then cold-emailed researchers and professors we found online who specialized in the disciplines with few sign-ups. We also cold-emailed geoscientists across disciplines at minority-serving institutions in the U.S. (i.e., Historically Black Colleges and Universities; Hispanic-Serving Institutions), at research institutions located in countries not well-represented by the sign-ups, and from databases such as “Water Researchers of Color” (Hampton & Byrnes, 2020). We cold-emailed over 140 scientists asking them to join the Collection or distribute the information to their colleagues or networks. After several months of the advertising campaign, we closed the registration form in July 2021 when most writing teams were actively writing or had completed their first drafts. However, we included a contact email for people who were still interested in getting involved, so involvement was never fully closed. Writing teams also brought in additional writers at times, and they were integrated into the Collection. Ultimately, the ICON Collection to date has 19 out of the 25 AGU sections represented. The 6 sections that are not part of the collection are Atmospheric and Space Electricity, Geodesy, Mineral and Rock Physics, Nonlinear Geophysics, Planetary Sciences, and Study of the Earth’s Deep Interior. We encourage their inclusion, and if there are researchers in these disciplines that want to contribute an article, they can reach out to the Collection leadership team to get started.

2.5 Writing

The writing process operated within a framework set forth by the leadership team and supported by section champions, but the writing teams intentionally operated independently. The leadership team formed writing teams within articles based on themes submitted, collated, and then ranked by the writers. Up to three writing teams each wrote an independent theme-based section, and these sections were collated into a single commentary article. Most writers did not know the other people in their assigned team. Each writer came to the project with a firm understanding of their field of work and an interest in ICON principles. Whenever possible they brought in additional expertise to discuss the challenges, tools, and opportunities to advance their field. What was new and sometimes more difficult to connect were the ICON principles to these challenges and opportunities. The leadership team met upon request with section champions and writing teams and provided clarifications and links to guidance materials frequently. Most communication with the leadership team was done over Slack and email, including bi-weekly check-ins, and many writing teams held frequent virtual meetings for collaboration without leadership team members. The emphasis on communicating within writing teams rather than with the leadership team was intentional. We wanted the articles to reflect the perspectives and opinions of the writers and their experiences. Allowing for flexibility in interpretation of the article goals and themes allowed for the writers to more clearly emphasize what stood out specifically to them. In some cases this led to repetition by multiple writing teams within the single article, which was a valuable indicator of the importance of a topic to the discipline.

The maximum level of interaction between the leadership team and the writers came during two rounds of revisions to each draft. The feedback provided by the leadership team on the drafts was focused on the following:

- General light editing (i.e., clarity, coherence, critical grammatical errors)
- Verifying there were examples for points made (i.e., describing “how” not just “what”)
- Clarifying ICON definitions and descriptions as needed (e.g., ‘networked’ is more than conference interactions)
- Verifying the overall article framing was around ICON (i.e., specific principles are called out and applied)
- Suggesting specific text/topics, improvements, ideas, and ways to think about components differently.

The leadership team also provided front-end language for the titles, abstracts, and introductions of the articles to help with cohesion and to provide the reader with context and connection to the rest of the ICON Collection. The leadership team provided the AGU journal requirements and left the submission duties to the writing team. The final submission was determined by the writing teams. Since the articles for most sections were made up of individual pieces written by independent teams, author order is often alphabetical and readers should not necessarily interpret author order as indicative of contribution.

3 Results: Understanding the collaborative writing process

3.1 Composition of the writing teams

When recruiting the participants for the Collection, we asked them to fill out their demographics to be aware of the scientists' background behind the commentaries. We compared the initial group of participants who expressed interest to be part of the collection (sign ups) with the final authors who wrote articles (Figure 1). From the final list of authors who participated in the ICON Collection, 24% did not register through the form that we used during the recruitment process (Section 2.4). Figure 2 displays six categories of demographics. For authors who selected more than one race/ethnicity, each race/ethnicity was counted separately. The most common gender identity and race/ethnicity across both sign ups and writers was male and “White or Caucasion.” “South or Southeast Asian” was the second most common race/ethnicity. The two most common races/ethnicities that were selected at the same time were “White or Caucasian” and “Hispanic and/or Latinx”. Of the 5.1% of “Hispanic and/or Latinx" authors in Figure 2f, half also checked the box for “White or Caucasian”. The most common age range of sign ups who expressed interest in the Collection and who participated in the process was 30 to 39 years. This correlates well with almost half of the authors identifying as early career scientists.

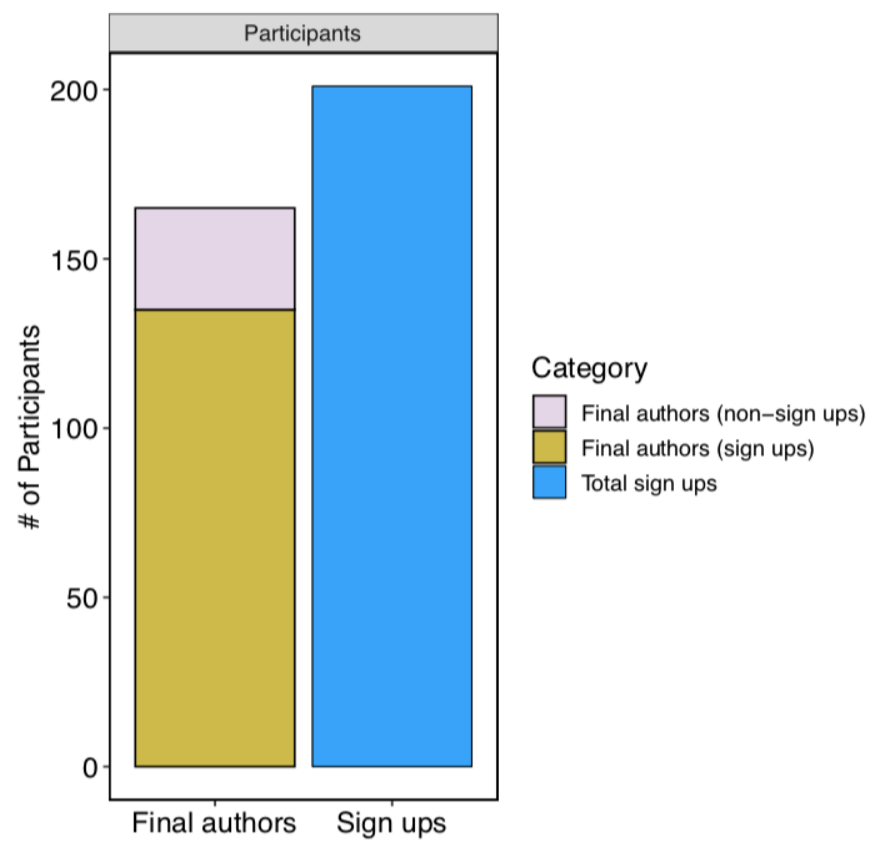

Figure 1: Number of final authors who wrote articles (left), divided between the participants who signed up at the beginning of the recruitment (lower) and the ones who did not sign up (upper); and number of people who originally signed up to be part of the collection.

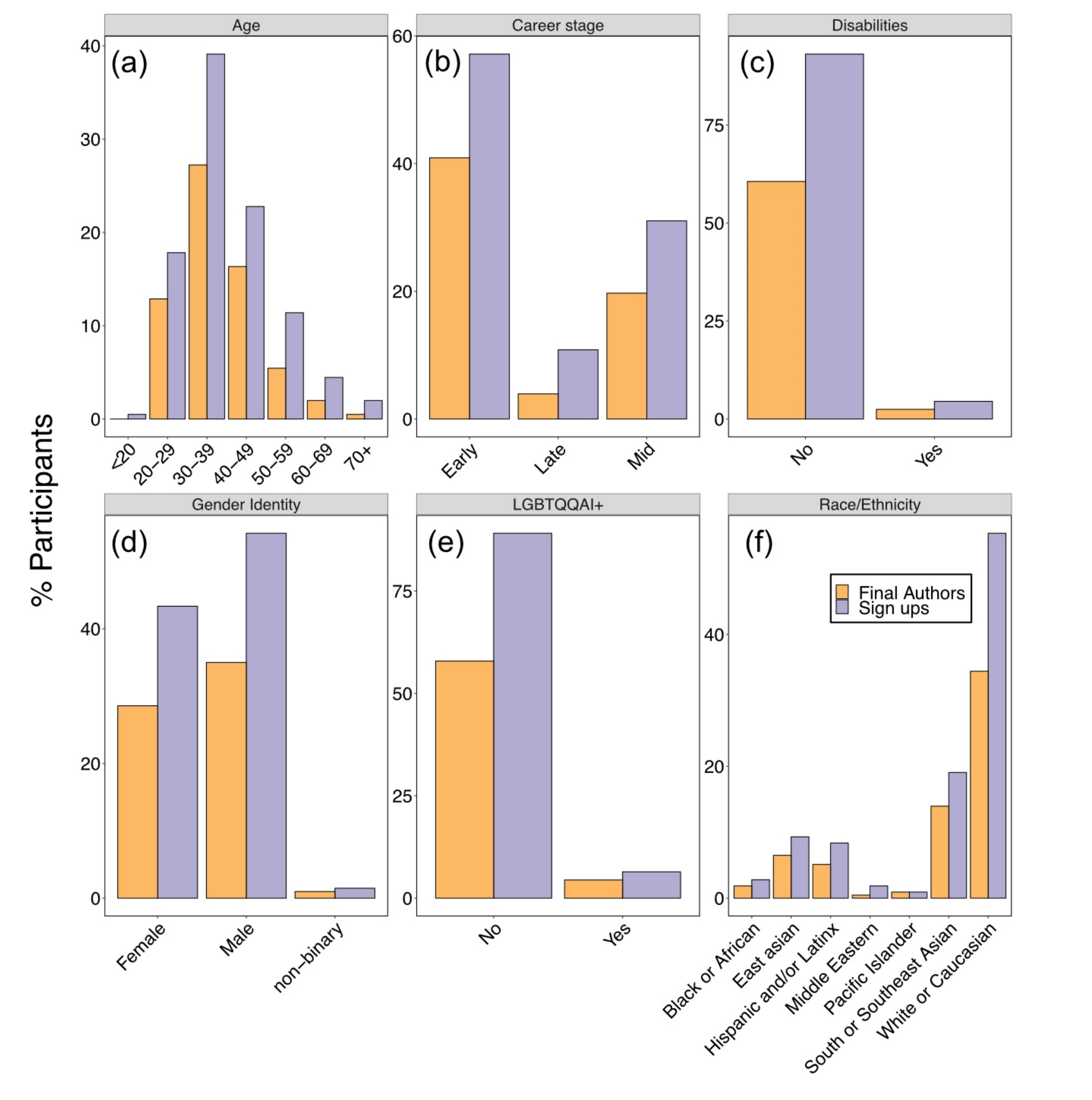

Figure 2: Age (a), career stage (b), disability (c), gender identity (d), LGBTQAAI+ identity (e), and race/ethnicity (f) from the participants who originally filled out the sign up form (representing the 100%) and the final authors who wrote articles for the Collection.

To assess how the demographics of the ICON Collection participants compare to AGU members, we compared the final authors' demographics with the 2020 AGU's Diversity, Equity and Inclusion dashboard data collection (AGU, 2021) (Fig. 3). Authors without demographics data were categorized as "unknown." To have comparable categories in the race/ethnicity data, we re-grouped the ICON data from East Asian, Middle Eastern, and South or Southeast Asian into Asian or Asian American. An important difference between the ICON Collection and AGU race/ethnicity is the AGU race/ethnicity is U.S. only, whereas the Collection data is from all the ICON participants. From the total authors who submitted commentaries to the collection and submitted demographics information, 55% are based outside the U.S. In the context of the total 163 authors in the collection, this translates to at least 20% of authors are based outside the U.S.

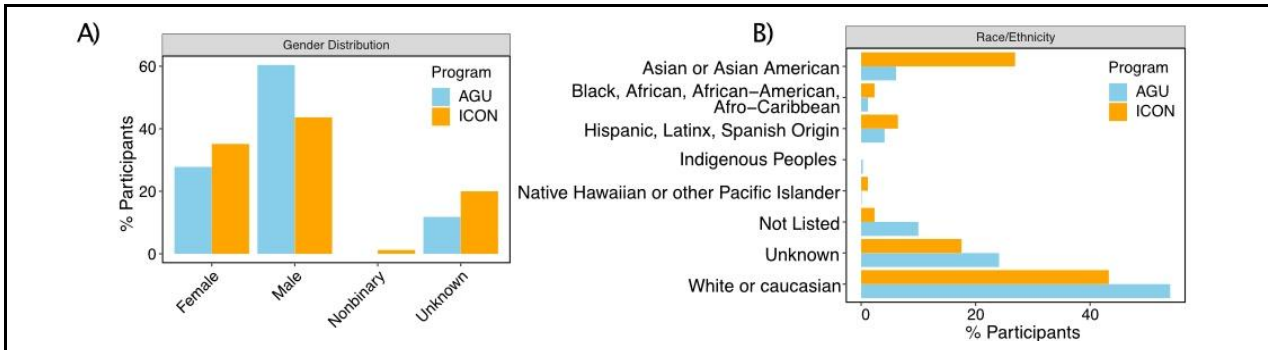

Figure 3: Gender identity distribution (a) and race/ethnicity distribution (b) from the authors in the Collection (orange) and AGU's 2020 Diversity, Equity and Inclusion dashboard data collection (blue)(AGU, 2021).

3.2 Group dynamics

The ICON Collection leadership team received feedback from participants to understand more about their experiences of writing in this crowdsourced approach. We heard from 64 of the 163 authors. Of those 64, 90% would like to get involved in another crowdsourced open science collaborative writing opportunity. Although they began this process without knowing the people in their writing teams, over 80% said that in their writing teams their ideas and perspectives were heard and included; they were included in making decisions and felt satisfied with how decisions were made; they felt they could voice contrary opinions and their opinions were valued; and they felt respected. One goal of this effort was creating a foundation for future collaborations, and 75% believe that working on the Collection created connections with people in their field that can be fruitful to future collaboration. One of the writing teams has already begun working on a new project, and over 70% have a project planned or would like to work again with the people they met through this experience.

The same 64 participants also provided input on what the writing teams and the leadership team could do to create a more inclusive culture and a more equitable culture. Several recurring themes emerged from the feedback: (1) Create opportunities for social engagement and communication early in the process to build trust and better understand people's working styles and needs; (2) Increase diversity, including international representation, and relatedly, improve scheduling for different time zones and create space for different languages; (3) Facilitate more direct communication between the leadership team and the authors; (4) Provide more clarity on authorship guidelines and verify agreement of all participants at the start of the process; (5) Increase advertisement of opportunities to get involved; (6) Provide examples of expected outcomes; (7) Make sure collaboration tools are accessible by all participants; (8) Increase use of virtual meetings rather than relying on written tools; and (9) Provide more time for participants to accomplish tasks. These themes specifically tie into 'Coordinated', 'Open', and 'Networked' and illustrate not only important areas to improve upon in the future but also the value in critically assessing our approaches and tools through the ICON lens - not just at the beginning of the process, but repeatedly throughout the process.

It is important to recognize that even with intentionally designing the process of writing the Collection to align with ICON, we saw that at times people felt like they were not being fully heard depending on the dynamics of their team, or that differences in time zones were prohibitive for coordinating meetings with writing teams. As described above, we placed individual contributors in writing teams within their discipline based on a ranking system of possible themes of interest, and although the responsibility to make sure teams were coordinating well was given to each section champion for the section, retrospectively it may have been useful to establish teams in a way that was structured by time zones or more involved based on communication styles. For some articles, no writer volunteered to be section champion, so a leadership team member stepped into that role. This approach did not hold the same weight as having a champion from the discipline who could understand more nuances of the discipline-specific dynamics and was available to be more hands-on. For a collection of this size, it is not feasible for five leadership team members to structure the full list of authors into individual personalized groups, but it would have been helpful to have more section champions and have each of those champions be more involved in establishing the teams based on the dynamics they saw. This likely would have addressed some of the comments that mentioned individuals who were more outspoken or more senior within their career stages had a disproportionate voice within their groups. Groups that were, by chance, structured by earlier career stage individuals seemed to have had pleasant experiences with their opinions being heard and valued, and thus providing support with a more involved grouping dynamic may have helped mitigate some of these issues. It also may have been helpful to hold a virtual meeting space where the leadership team could oversee the introduction and dynamic of the different writing teams, as some people noted that they would have liked a more involved role from the leadership team to establish the teams.

Interestingly, even within a group of writers focused on ICON and using an ICON approach to the Collection, we had some difficulties regarding authorship order and authorship contributions. This suggests that even people who recognize the importance of what the ICON framework represents struggle with implementing it on a personal level or fail to understand what it represents as a whole. This experience demonstrates that more effort is needed to shift the scientific culture towards a more open, equitable, and collaborative perspective of authorship and other common metrics of success.

Finally, the bias towards a lack of underrepresented groups and marginalized communities within STEM fields is prevalent within this ICON Collection even after the leadership team's attempts to reach out to specific groups and organizations in an effort to increase the overall representation. We recognize that not all voices in the geosciences are represented in this Collection, and that greater efforts must be taken to capture these voices. It is possible that some scientists we reached out to from marginalized groups could not afford to take time to write in this collection, and that further placing the onus on these communities to navigate a way to become involved seems like an inappropriate way of making their voices heard. In an effort to provide greater inclusivity within future collections, financial support or other tangible resources may help mitigate the disparity in the demographics. As it was put by one of the writers who provided feedback: “we still have a ways to go.” It is our hope that the ICON Collection serves as a primer to help people understand what we need to move towards, and how it can be done to enable scientific pursuits to be more aligned with the foundational goals of ICON.

4 Results: Understanding ICON

4.1 Defining ICON

Throughout the writing process and most clearly during the leadership review of the first drafts of the articles, it was clear that there was variation in how people understood some of the ICON principle definitions. Teams were provided with written definitions at the beginning of the process in the article advertising involvement in the ICON Collection (Goldman et al., 2021). They were also provided the link to an example of ICON in practice on the website for the Worldwide Hydrogeochemistry Observation Network for Dynamic River Systems (WHONDRS; https://www.pnnl.gov/projects/WHONDRS/icon-fair-framework). There were three recurring experiences across the writing teams: (1) Teams expanded definitions to better fit their experiences; (2) Teams wrote extensive content related to a specific ICON principle but did not realize that the content was related to the principle; and (3) Teams misunderstood or partially understood the definition of one or more ICON principle. Having teams expand definitions to better fit their experiences was an outcome we hoped would occur during the writing process, and the content and nuances in the articles is valuable in understanding how different disciplines engage with ICON. Teams writing content without realizing it applied to a principle or misunderstanding a principle occurred most frequently with the ‘Networked’ principle. Many first drafts identified engaging with colleagues at conferences and workshops as the source of ‘Networked’ in their discipline and separately wrote about the importance of mutual benefit and stakeholder engagement without linking it to an ICON principle. This highlights that an important component of expansion of the ICON framework is clear communication about the meaning and foundation behind each principle. When a concept is already embedded in someone’s mind, it can be challenging to incorporate a broader or different definition. This was also a challenge with the ‘Open’ principle, which required people shifting from the concepts of open data or open publishing to open and FAIR science throughout the research lifecycle. Iterating with the writing teams during the two rounds of leadership team-provided feedback was a valuable way for the leadership team to reflect and learn from how writers were interpreting the ICON principles and to provide guidance when appropriate.

4.2 Common themes

We found common themes across people’s experiences creating the articles and across the key points defined in the articles. Although all articles aimed for the same goal of exploring ICON science within their field, in practice, each discipline is at different stages of enacting science following ICON principles. For example, some sections focused on the difficulties of collecting and sharing data and how the cultural and historical hierarchies within the field make this difficult. Other sections highlighted struggling with an excess of publicly available data that was not coordinated and as such, unavailable for meta-analyses or cross-study interpretations. However, across all of the articles, even for fields actively implementing ICON principles, there was a recognition that there are opportunities for growth and improvement that will ultimately help the discipline as a whole.

Perhaps the most common theme across manuscripts was the two-fold perspective that the geosciences would benefit from more use of ICON principles, but that using these principles also presents risks. For example, several articles mentioned the risk of "parachute science" and "helicopter science" in which samples and/or data are extracted for the benefit of researchers without providing commensurate beneficial outcomes to those providing resources and/or impacted by research outcomes (Minasny et al., 2020; Stefanoudis et al., 2021). This occurs most often in the context of researchers from wealthier countries traveling to developing or lower income countries and collecting data and resources for the purpose of taking it back to their original institutions. This results in detrimental effects to the community that had helped provide the samples/data/resources and divorces the scientific products from the locations, cultures, and communities from which they are sourced, often resulting in a lack of critical insights into the systems and environments and subsequently incomplete and improperly analyzed data.

In a related theme, many manuscripts highlighted the need for greater equity in science and discussed ways in which this could be achieved. Across manuscripts, it is clear that the geosciences community feels strongly that the risks of ICON must be considered and minimized through careful planning and community engagement. The issues can be context dependent and there is a need to work with stakeholders to understand risks and generate/use mechanisms that minimize these risks. This risk evaluation is part of the 'Networked' component of ICON, which is focused on pursuing research in a way that is mutually beneficial for the primary research team and multiple stakeholders involved in and/or impacted by the work. The repeated focus across manuscripts on the value of mutually beneficial research indicates a need to more fully develop and formalize strategies to achieve the ICON vision for 'Networked' science. This goes hand-in-hand with increasing equity in science by using ICON principles to increase opportunities for researchers across diverse settings in a way that is mutually beneficial for those engaged and impacted.

Ultimately, although each of the sections identified challenges and risks within their fields, there was a general consensus that implementing ICON principles will lead to successful scientific advances. It is our hope that with the ICON Collection, different fields from the geosciences can understand that they are all attempting to achieve similar goals, and that there is much to learn by exchanging knowledge of and experiences with the implementation of ICON principles.

4.3 Perceived benefits outweigh costs of ICON science

As with every approach to doing science, the use of ICON principles comes with both costs and benefits. The benefits should outweigh the costs for any approach that is used. Otherwise, there is no motivation to use a given approach. It is thus important to assess the costs and benefits of all four ICON principles. A formal accounting of all costs and benefits is, however, far beyond the scope of our current efforts. Instead of a formal analysis, each writing team was asked to place each ICON letter within a cost-benefit space. This space was defined by a cost axis and a benefit axis, both ranging from 0-10 (Fig.4). The placement of the letters was inherently subjective and meant to represent each team's perception of ICON costs and benefits. Upon completion, we visually estimated the location of each letter along each axis to the nearest quarter point. This visual approach was deemed suitable, instead of a more precise method, given that the teams placed the letters by simply dragging and dropping them on the computer screen.

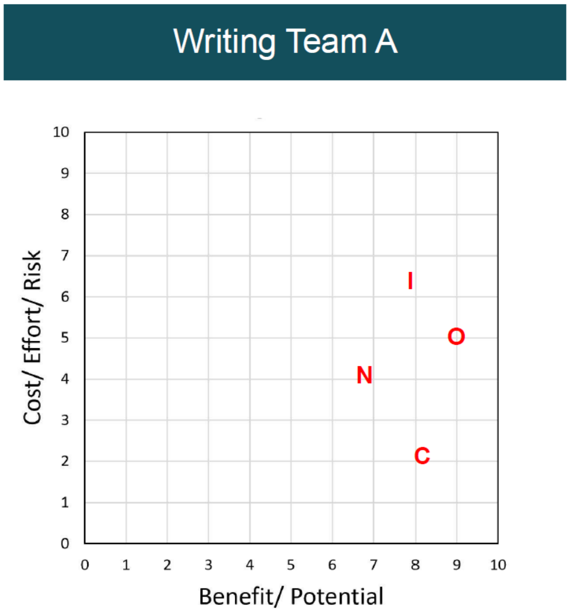

Figure 4. An example cost-benefit plot. Each writing team placed each letter of ICON in the two dimensional space to reflect their perception of the costs and benefits of using the associated principle.

Our analyses of the perceived costs and benefits clearly show that writing teams felt the benefits of all four ICON principles outweigh the associated costs (Fig. 5) and that variation in perceived costs was higher than variation in perceived benefits (Figs. 5a,b, 6). The cost distributions were all centered near ~5-6, while the benefit distributions were centered ~8-9. The median benefit was significantly higher than the median cost when pooling data across all four letters and across all teams (Two-tailed Wilcox test: $W = 2273.5$, p-value < 0.0001). Not surprisingly, the costs and benefits varied across teams in the same section/article, and the analyses summarized in Figure 5a,b do not directly account for this among-team variation.

To directly link perceived costs and benefits, we calculated the cost-benefit ratio for each ICON principle within each team. For all four ICON principles the cost-benefit ratio was significantly less than 1 (Fig. 5c), again showing that perceived costs are lower than perceived benefits. This was evaluated with a one-sided Wilcox test for each ICON principle: for 'Integrated', $V = 21$, p-value < 0.0001; for 'Coordinated', $V = 14$, p-value < 0.0001; for 'Open', $V = 6$, p-value < 0.0001; for 'Networked', $V = 55$, p-value < 0.001. Collapsing all team scores across all eight variables (one cost and one benefit for all four ICON principles) via a principal component analysis (PCA) showed that teams varied primarily in terms of the perceived costs of ICON (Fig. 6). This is consistent with the cost distributions being broader than the benefit distributions (Fig. 5a,b).

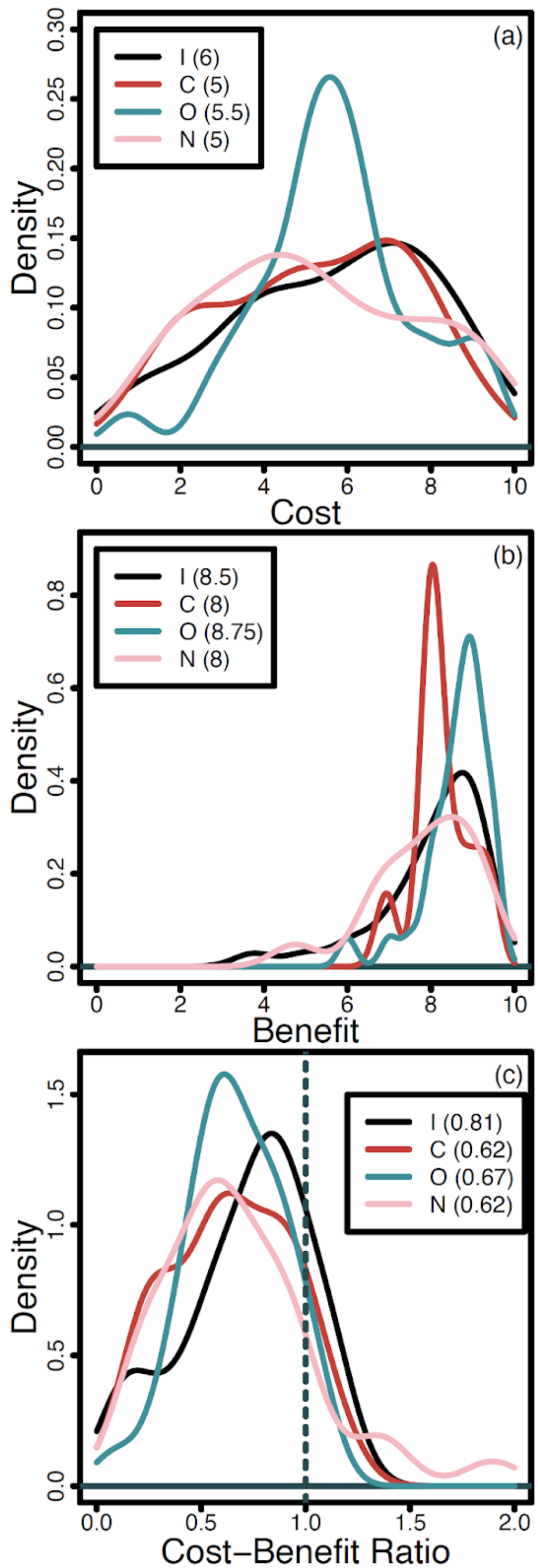

Figure 5. Writing teams perceived the benefits of ICON to be higher than the costs of ICON. Distributions of costs (a), benefits (b), and their ratio (c) for each ICON principle are summarized as kernel density functions. On each panel the median value for each distribution is given in the legend. Benefits are significantly higher than costs, and the cost-benefit ratios are significantly lower than 1 (see text for statistics).

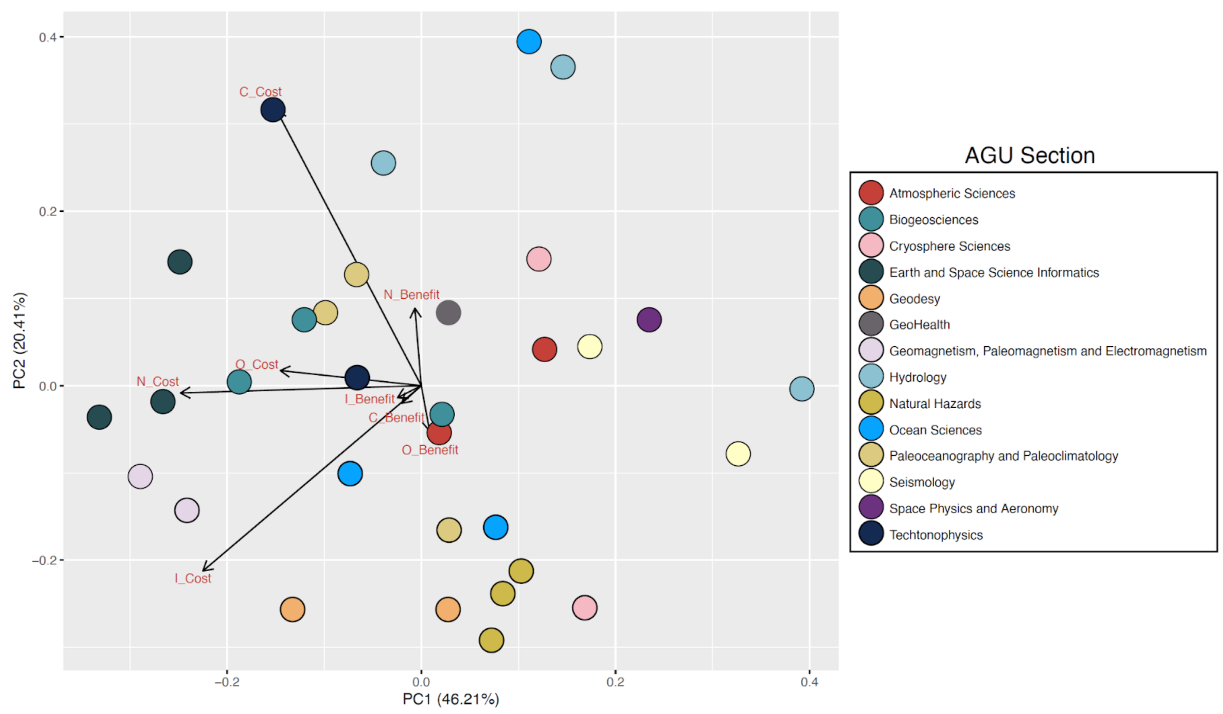

Figure 6. Teams varied most in their perceptions of the costs of using ICON principles. Perceived benefits were also generally high (Fig. 5b) and showed little variation among teams. These inferences are based on the cost-associated arrows being much longer than the benefit-associated arrows; arrow length is proportional to the loadings of those variables on each of the first two principal component (PC) axes. Each filled circle represents one writing team, with colors indicating the associated AGU section. Larger distances between any points indicates larger differences in their perceived costs and benefits of using ICON principles; teams within some sections cluster closely while others are divergent.

It is encouraging that across diverse geoscience disciplines there is a consistent perspective that the intentional use of ICON principles outweighs the associated costs. In addition, participants indicated that their perspective on the importance of ICON principles changed through the writing process for this special collection. Specifically, many participants indicated an increase in their perceived importance of intentionally using ICON principles. It is important to recognize, however, that perceived benefits may not all be currently available. That is, some perceived benefits may be thought of as potential benefits presumably via careful implementation that minimizes negative outcomes. We cannot quantify this at present, however, because the cost-benefit analysis did not attempt to parse current versus potential benefits. Future assessments may consider doing so.

In addition, the higher level of variation in perceived costs (relative to the variation in perceived benefits) indicates a need for deeper understanding of the costs of ICON. We emphasize that in the analysis, the interpretation of costs was not constrained. Each team interpreted the meaning and scope of ‘costs’ as they felt was appropriate. This could have led to variation among teams, though teams were also free to interpret ‘benefits’ as they felt appropriate. In turn, we hypothesize that higher variation in perceived costs was due to ‘costs’ spanning a more complex suite of considerations than ‘benefits.’ For example, participants noted potential risks of using ICON principles that go beyond direct financial and labor costs (Section 4.2). To help evaluate the landscapes of perceived costs and benefits, it would be useful to gather information on the identities and relative importance of specific costs and benefits. More generally, our observations collectively highlight the need to better understand and minimize the inclusive costs and risks of using an ICON approach. As discussed below, the ICON Science Cooperative has been launched to help address these needs.

5 Outcomes

5.1 Next steps identified within and across disciplines

Each of the ICON Collection’s individual articles provide next steps and actions that can move each discipline forward. In summation these recommendations and suggestions offer a pathway to continue learning about ICON principles to support advancing science across domains. The steps described could be divided into three themes: funding, infrastructure, and focused community engagement efforts.

Many sections’ articles pointed out the need for not only government research funding, but also funding from private and NGOs that enforces and emphasize policies that support the ICON principles. Almost all the Collection’s articles included a suggestion to engage citizen science and to equip it with funding. Other funding related needs were mentioned in the Cryosphere Science article, including support for new types of undergraduate research experiences that can accommodate those unable to travel but who can conduct remote data analysis (Brügger et al., 2021).

Under the infrastructure theme, suggestions included the need for better coordination among scientists to establish data standards, centralized and shareable data and equipment, and better understanding of leaders of the initiatives. The Collection’s Space Physics and Aeronomy article described a unique aspect of infrastructure in which memorandums of understanding (MOU) and agreements to host exchange programs can provide benefits that align with ICON (Sur, 2021). These agreements could increase ‘Coordinated’ and ‘Networked’ efforts, instead of encouraging competition that can be detrimental to the advancement of the field and to the students and early career scientists. The Collection’s Near-Surface Geophysics (NSG) article draws on a recommendation from the National Academies of Science, Engineering, and Medicine to provide access to NSG instrumentation from a central NSG Facility (Salman et al., In prep.).

There was agreement across articles that engaging with local communities was an important mechanism aligned with ICON principles, particularly ‘Networked,’ that is needed to uphold the societal value for science. The ICON Collection’s Hydrology and GeoHealth articles both note the importance of engaging the public interest in critical issues of local interest like water quality (Barnard et al., In prep.; Acharya et al., 2021). The Collection’s Biogeosciences article encourages the adoption of “people-centric” approaches to build research capacity, understand cultural nuances, and promote research community engagement with open fair research practices (Dwivedi et al., 2021). Several articles point out parachute science, discussed above, and instead encourage developing a relationship with local stakeholders, land stewards, and others, valuing their expertise, embracing the opportunity to learn from local or indigenous knowledge, and providing value back to them. The Paleoclimatology and Paleoceanography article describes “true collaboration,” as “co-develop[ing] mutually beneficial projects with the local community, aligning outcomes with both of their goals” (Belem et al., In prep.).

5.2 The ICON Science Cooperative

Pursuing research that fully embodies and uses all ICON principles is challenging, and there is a need to provide resources that help reduce these challenges. The ICON Science Cooperative (https://ICON-science.pnnl.gov) was launched to help meet this need. The mission of the cooperative is to “to enable researchers from all science domains to implement ICON science in a way that is mutually beneficial to the broader science community, thereby accelerating the pursuit of transferable results and enhancing scientific equity.” This mission underlies the cooperative’s long-term vision, which is “a future world in which researchers across all of science study, improve, and use ICON principles.” Researchers and other stakeholders at any career stage are encouraged to work with the cooperative in either or both of two primary modes of engagement. In one mode, the cooperative can help researchers more fully use ICON in their work. This can be done at any point in the research lifecycle, from proposal development to the modification of existing projects. In the second mode of engagement, researchers and any other interested stakeholders can work with the cooperative to help study ICON principles with the goal of improving how they are used. A key goal of this second mode of engagement is helping to develop open resources that help researchers use ICON principles in their work. In either mode, interested individuals and/or organizations can engage the cooperative through numerous mechanisms, ranging from informal discussions to formal collaboration. The cooperative can also host visiting researchers/stakeholders to enable mutual learning about how to best implement ICON science across diverse settings. Details on how to engage are provided at the ICON Science Cooperative website linked above.

As discussed above, manuscripts contributed to the ICON Collection often focused on needs and opportunities associated with the ‘Networked’ component of ICON. This is potentially the most challenging component of ICON because it requires understanding and meeting the needs of multiple stakeholders to achieve mutual benefit. Associated needs and benefits are often subjective and may be in conflict across stakeholders. This has the potential to lead to difficult situations for researchers, who are often not trained in how to find common ground among or even assess multiple stakeholder needs. As such, the ICON Science Cooperative will likely need heavy focus on developing guidance and other resources around the vision for and implementation of ‘Networked’ science. There is, however, a need to develop strategies for using all four components of ICON in a way that maximizes benefits and minimizes risks. While the cooperative will leverage other efforts that touch components of ICON (e.g., The Center for Open Science), the cooperative addresses the unique challenge of simultaneously using all ICON principles. The cooperative is therefore one mechanism (among many) needed to advance the use of ICON science throughout the geosciences and beyond.

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Open Research

The data and R scripts (version 3.6.1) used for plotting and statistics are available at https://github.com/stegen/ICON_Science_Cost_Benefit. The data associated with demographics are not posted to protect the anonymity of participants.

References

Acharya, B.S., Ahmmed, B., Chen, Y., Davison, J.H., Haygood, L., Hensley, R.T., et al., (2021). Hydrological Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508463.3

AGU. (2021). AGU's Diversity, Equity and Inclusion Dashboard: Baseline Data across AGU Programs. Retrieved from https://www.agu.org/-/media/Files/Learn-About-AGU/AGU_DEI_Dashboard_2020_baseline_demographic_snapshot.pdf

Barnard, M., Emani, S., Fortner, S., Haygood, L., Sun, Q., White-Newsome, J., & Zaitchik, B. (In prep.). GeoHealth Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science.

Belem, A. L., Bell, T., Burdett, H., Ibarra, D., Kaushal, N., Keenan, B., et al. (In prep.). Paleoclimatology and Paleoceanography Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science.

Brügger, S., Jimenez, A. A., Ponsoni, L., & Todd, C. (2021). Cryosphere Sciences Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508421.1

Dwivedi, D., Santos, A. L. D., Barnard, M. A., Crimmins, T. M., Malhotra, A., Rod, K. A., et al. (2021). Biogeosciences Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508474.2

Goldman, A. E., Emani, S. R., Pérez-Angel, L. C., Rodríguez-Ramos, J. A., Stegen, J. C., & Fox, P. (2021). Special Collection on Open Collaboration Across Geosciences. *Eos*, *102*. doi:10.1029/2021EO153180

Hampton, T., & Byrnes, D. (2020). Water Researchers of Color experts in their fields. Retrieved October 20, 2021, from https://blogs.egu.eu/divisions/hs/2020/09/09/water-researchers-of-color-experts-in-their-fields/

Hills, D., Damerow, J., Ahmmed, B., Catolico, N., Chakraborty, S., Coward, C., et al. (2021). Earth and Space Science Informatics Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508448.2

Minasny, B., Fiantis, D., Mulyanto, B., Sulaeman, Y., & Widyatmanti, W. (2020). Global soil science research collaboration in the 21st century: Time to end helicopter research. *Geoderma*, *373*, 114299. doi:10.1016/j.geoderma.2020.114299

National Academies of Sciences, Engineering, and Medicine. (2018). Open Science by Design: Realizing a Vision for 21st Century Research. Washington, DC: The National Academies Press. doi:10.17226/25116

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Salman, M., Slater, L., Briggs, M., & Li, L. (In prep.). Near-Surface Geophysics Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science.

Sharma, S., Dahal, K., Nava, L., Gouli, M. R., Talchabhadel, R., Panthi, J., et al. (2021). Natural Hazards Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508384.1

Stefanoudis, P. V., Licuanan, W. Y., Morrison, T. H., Talma, S., Veitayaki, J., & Woodall, L. C. (2021). Turning the tide of parachute science. *Current Biology, 31*(4), R184–R185. doi:10.1016/j.cub.2021.01.029

Sur, D. (2021). Space Physics and Aeronomy Perspectives on Integrated, Coordinated, Open, Networked (ICON) Science. *Earth and Space Science Open Archive*. doi:10.1002/essoar.10508451.1

U.S. DOE. (2019). Open Watershed Science by Design: Leveraging Distributed Research Networks to Understand Watershed Systems Workshop Report (No. DOE/SC-0200). U.S. Department of Energy Office of Science. Retrieved from https://ess.science.energy.gov/open-watershed-workshop/

Wilkinson, M. D., Dumontier, M., Aalbersberg, Ij. J., Appleton, G., Axton, M., Baak, A., et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, *3*(1), 160018. doi:10.1038/sdata.2016.18