Authorship and contribution recognition in infrastructure-scale Earth science collaborations

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Abstract

Community-driven collaborative initiatives across palaeoclimate, oceanography, and Earth system science have transformed how scientific knowledge is generated, integrated, and interpreted. Proxy synthesis efforts, climate model intercomparison projects, and scientific drilling programmes increasingly function as collaborative scientific infrastructures sustained by distributed intellectual labour spanning data stewardship, harmonisation, workflow development, methodological arbitration, coordination, governance, and scientific leadership. However, prevailing systems of authorship and academic recognition remain largely designed around paper-centric models of contribution developed for smaller and more time-bounded research projects. As a result, many forms of foundational and integrative labour essential to infrastructure-scale science remain inconsistently recognised within conventional attribution systems. Drawing on our own experiences from collaborative Earth science initiatives and community survey responses, we show that this mismatch has implications not only for fairness and career progression, but also for scientific accountability, sustainability, and the long-term resilience of collaborative Earth system research. We outline emerging community adaptations and propose practical pathways toward more infrastructure-aware approaches to scientific recognition, aimed at aligning attribution systems with the realities of collaborative, infrastructure-scale science.

Introduction

Over the past two decades, Earth system science has undergone a profound transformation in how scientific knowledge is produced as our community has self-organised and redefined collaboration frameworks. Community-driven collaborative palaeoclimate, oceanographic, and Earth system initiatives now underpin many of the frameworks through which past climate variability, Earth system sensitivity, and long-term environmental change are understood. Unlike conventional project-based research, these initiatives are often international in scope, open to broad community participation, and sustained through shared scientific goals, collective stewardship, and long-term coordination rather than a single principal investigator, institution, or funding source (**Fig. 1**). They increasingly function as collaborative scientific infrastructures that bring together distributed datasets, expertise, and methodological frameworks across institutions and continents. These infrastructures also generate scientific value beyond publications through shared datasets, analytical workflows, community standards, software, and other resources that may be reused, cited, and adopted across the wider research community.

This collaborative landscape spans data generation, data synthesis, and infrastructure and modelling activities that together support the production of Earth system knowledge (**Fig. 2**) Scientific data collection programmes (e.g. ocean and continental drilling programmes), not only continue to generate globally distributed records but also provide decades of accumulated observations, samples, and datasets that form the empirical backbone of many synthesis and modelling efforts. Proxy synthesis efforts[1–3] integrate heterogeneous datasets across archives, regions, and timescales to address broader Earth system questions, while model intercomparison efforts[4–7] and community data infrastructures[8–11] provide the standards, tools, frameworks, and coordination necessary for large-scale integration and interpretation. Together, these initiatives have enabled scientific questions to be addressed at scales impossible within individual projects or research groups alone. Increasingly, scientific advances emerge not from isolated datasets or individual studies, but from the collective integration, harmonisation, and interpretation of knowledge distributed across communities.

As a result, collaborative Earth science has evolved from relatively discrete, project-based studies toward increasingly coordinated and persistent forms of collaboration[1,2,5,12] (**Fig. 1**). What may begin as a finite scientific project can develop into a longer-term programme, evolve into a synthesis network spanning multiple datasets and communities, and ultimately become a community infrastructure supporting successive generations of scientific outputs. Many contemporary initiatives therefore extend beyond the lifespan of individual grants, publications or participating researchers, relying instead on sustained community engagement, governance structures, data stewardship and shared methodological practices. Rather than replacing traditional project-based research, these collaborative efforts increasingly provide the infrastructure within which individual projects are conceived, conducted, and synthesised, creating interconnected scientific ecosystems that operate across multiple organisational scales.

Yet while collaborative Earth science has evolved toward infrastructure-scale research, systems for authorship, attribution, and academic reward have changed more slowly[13–18]. Existing recognition frameworks remain strongly centred around discrete publication outputs, first- and last-author visibility, and paper-specific definitions of contribution. These conventions were largely developed for smaller and more time- and effort-bounded forms of collaboration, where scientific labour was more easily linked to individual outputs and shorter project timescales. Modern collaborative synthesis science operates differently. Large initiatives increasingly depend on cumulative and often longitudinal forms of intellectual labour (e.g. data stewardship, harmonisation, workflow development, methodological arbitration, scientific leadership and governance, community coordination). These activities are essential to scientific outcomes, yet they frequently occur long before visible publications emerge and are often poorly represented within traditional authorship structures.

In many cases, the datasets, standards, and workflows that enable scientific discoveries and advances are themselves the product of years of collective effort. These contributions may receive recognition through citations, reuse, adoption by the community, or incorporation into subsequent research. However, these forms of recognition are often less visible within conventional publication-centred attribution and academic evaluation systems. This mismatch matters for several reasons. First, inadequate recognition can create inequities in career progression and disproportionately disadvantage contributors engaged in stewardship, infrastructure development and coordination roles[19,20]. Second, weak visibility of integrative labour obscures scientific accountability by making it difficult to identify how critical methodological and interpretive decisions were reached. Third, sustaining long-term collaborative infrastructures depends on continued community participation, and invisible or undervalued labour risks contribute to fatigue, disengagement and erosion of institutional memory. Ultimately, if the labour required to sustain collaborative infrastructures is not adequately recognised, the scientific systems upon which future synthesis depends may themselves become more difficult to maintain.

Here we examine how authorship and contribution recognition currently operate within collaborative Earth science initiatives and why existing models increasingly struggle to capture the realities of infrastructure-scale synthesis science[13,14]. Drawing on our experiences as participants and leaders within these palaeoclimate synthesis initiatives, alongside insights from a targeted community survey of researchers involved in synthesis, modelling and drilling and data infrastructure efforts, we propose that future attribution systems would benefit from moving beyond purely paper-centric models toward more longitudinal, role-aware, and infrastructure-sensitive approaches to scientific credit, while recognising that scholarly impact may also accrue through data reuse, methodological uptake, community standards, software, and other forms of scientific infrastructure that extend beyond conventional authorship.

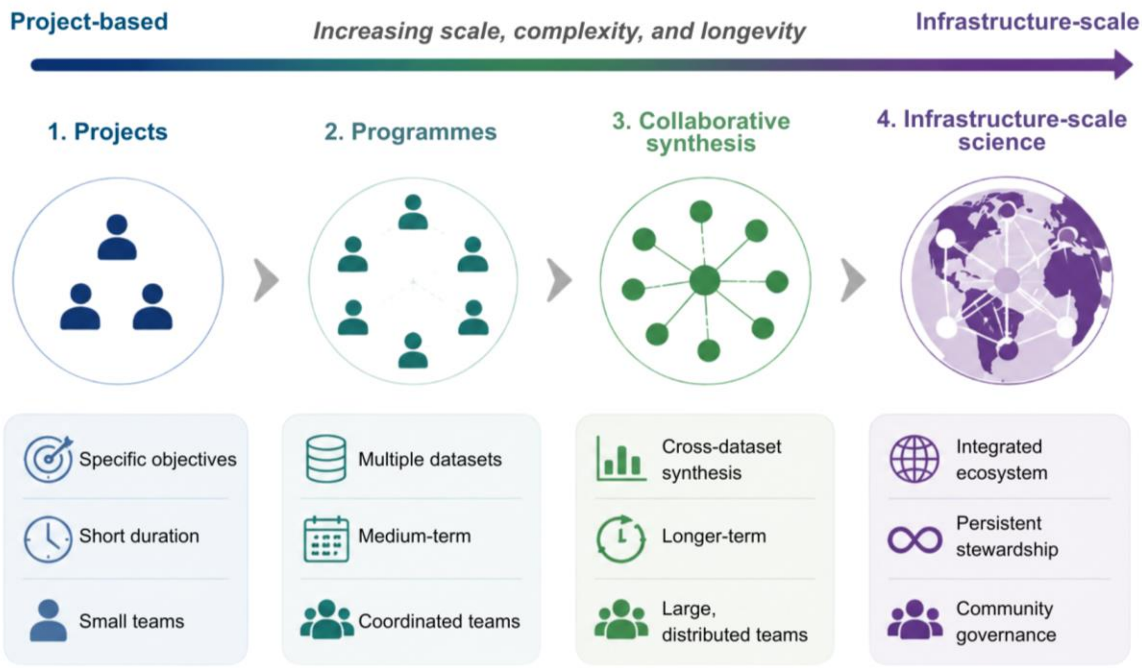

Figure 1: Schematic illustration of how Earth science collaborations can evolve from discrete, project-based studies toward increasingly persistent and interconnected forms of community-driven research. Individual projects may develop into programmes, synthesis

networks, and ultimately collaborative scientific infrastructures that support successive generations of datasets, methods, publications, and community activities.

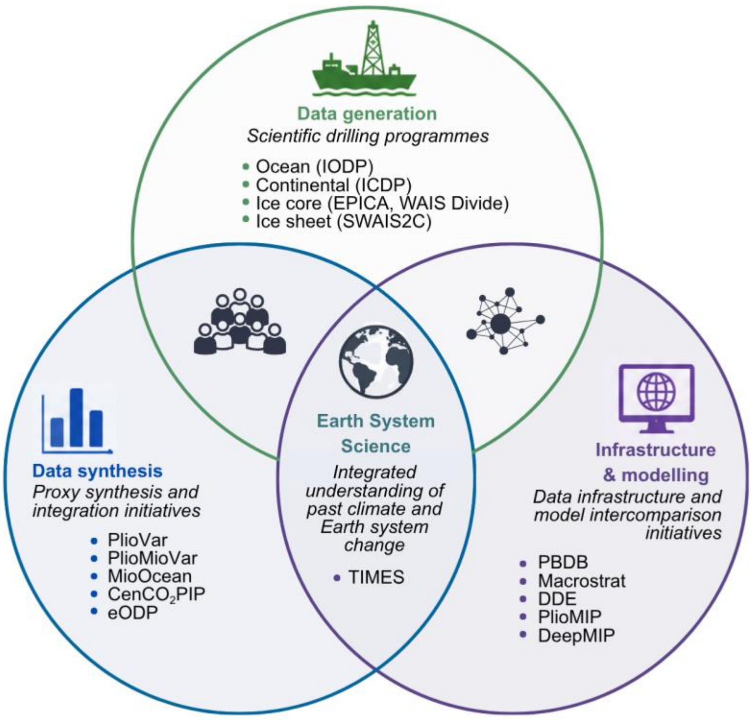

Figure 2: Interconnected collaborative infrastructure underpinning Earth system science. The list of initiatives shown are illustrative rather than exhaustive, and are presented as examples of collaborative scientific infrastructures, many of which have pioneered innovative approaches to recognising diverse forms of contribution. ***Acronyms:*** **IODP**, International Ocean Discovery Program; **ICDP**, International Continental Drilling Program; **EPICA**, European Project for Ice Coring in Antarctica[21]; **WAIS Divide**, West Antarctic Ice Sheet Divide Ice Core Project[22]; **SWAIS2C**, Sensitivity of the West Antarctic Ice Sheet to 2°C of Warming[23]; **PlioVar**, Pliocene climate Variability over glacial-interglacial timescales[1,24,25]; **PlioMioVar**, Pliocene and Miocene climate Variability over glacial-interglacial timescales[3,26]; **MioOcean**, Miocene Temperature Synthesis, **CenCO$_2$PIP**, Cenozoic Carbon Dioxide Proxy Integration Project[2]; **eODP**, Extending Ocean Drilling Pursuits[27]; **TIMES**, Time-Integrated Matrix for Earth Sciences[12,28]; **PBDB**, Paleobiology Database[11]; **DDE**, Deep-time Digital Earth[29]; **PlioMIP**, Pliocene Model Intercomparison Project[5–7]; **DeepMIP**, Deep-time Model Intercomparison Project[4].

From projects to collaborative scientific infrastructures

Historically, much of Earth science collaboration was organised around relatively discrete research projects with clearly defined objectives, timelines and outputs, often led by a single or small groups of investigators. While authorship decisions were sometimes contested, contributions could generally be linked to identifiable analyses, datasets or manuscripts. As collaborative Earth science has evolved toward long-term scientific infrastructures (**Fig. 1**), however, the relationship between scientific labour and publication outputs has become increasingly diffuse. Contemporary synthesis initiatives integrate multiple generations of contributors, continuously evolving datasets, and shared methodological frameworks, with outputs emerging not only through publications but also through databases, software, protocols, and community standards[30–32].

This shift has fundamentally altered the organisation of scientific work. Increasingly, the scientific challenge is not simply generating new data, but integrating, harmonising, and interpreting diverse forms of evidence across temporal, spatial, and disciplinary scales[12,28]. As initiatives expand in scale and duration, new forms of labour emerge that are essential to scientific progress but remain less visible within conventional publication-centred attribution systems. These include data stewardship, metadata harmonisation, workflow development, methodological arbitration, quality-control procedures, coordination across working groups, and community management. Such activities often require sustained expert judgement and substantial intellectual investment, yet they do not necessarily map onto discrete manuscripts or clearly bounded outputs. Importantly, many of these roles are cumulative and enabling rather than episodic. For example, contributors who establish harmonisation standards, resolve taxonomic inconsistencies, or develop reproducible workflows may shape dozens of downstream synthesis outputs without necessarily occupying prominent authorship positions in individual publications. Similarly, scientific leadership and governance roles frequently involve interpretive mediation, strategic direction, and coordination across disciplinary boundaries, all of which substantially influence scientific outcomes but remain difficult to represent within paper-centric contribution systems.

The transition from projects to infrastructure-scale science therefore represents more than an increase in collaboration size. It reflects a shift in the nature of scientific labour itself. Scientific progress increasingly depends upon activities that create and sustain the conditions under which synthesis becomes possible. These contributions are often distributed across many individuals, unfold over extended periods of time, and generate value collectively rather than through discrete outputs. This evolution parallels developments in other infrastructure-intensive fields such as astronomy, genomics, medicine, and high-energy physics, where collaborative research increasingly depends on long-term systems of coordination and stewardship[17,33,34]. However, Earth science has adopted comparatively fewer formal mechanisms for recognising infrastructure labour and distributed contribution, despite facing many of the challenges associated with large collaborative enterprises.

Existing authorship frameworks and their limits at scale

Authorship remains the primary mechanism through which scientific credit, accountability, and career advancement are assigned. Widely used guidelines emphasise substantial intellectual contribution, responsibility for content and participation in manuscript development[13,18]. More recently, contributor role frameworks such as the Contributor Roles Taxonomy (CRediT) have sought to improve transparency by making different forms of contribution more visible[15,17,35]. These developments have been important advances. Contributor taxonomies help move scientific recognition beyond simplistic interpretations of author order and acknowledge a broader range of activities including data curation, methodology and project administration[17,20,35-37]. For interdisciplinary research in particular, they provide greater clarity regarding how collaborative work is distributed.

To better understand how these frameworks are experienced within collaborative Earth science initiatives, we conducted a targeted anonymous survey of researchers involved in synthesis efforts, modelling initiatives, scientific drilling programmes and community data infrastructures (**Supplementary Dataset**). The survey intentionally targeted both contributors and initiative leaders in order to capture perspectives from individuals directly involved in the organisation, governance, and scientific outputs of these collaborations. Respondents represented a range of career stages, including early-career (37.5%), mid-career (31.3%) and senior researchers/professors (31.3%) (**Fig. 3a**). Most respondents reported that their contributions had been clearly recognised in publications arising from initiatives in which they had participated (67.7%), although approximately one-quarter reported only partial or unclear recognition (**Fig. 3b**). At the same time, relatively few respondents considered existing authorship frameworks fully adequate for capturing the full range of contributions made within collaborative initiatives (12.9%), with the majority indicating that current frameworks were only partially adequate (51.6%) or inadequate (25.8%) (**Fig. 3c**).

Respondents also recognised that collaborative initiatives depend upon a diverse range of contribution types extending well beyond manuscript preparation alone (**Fig. 4**). Activities associated with workflow and infrastructure development, data generation, coordination and management, synthesis and analysis, and data curation and stewardship were consistently ranked among the most important contributions for the success of collaborative initiatives. In contrast, manuscript preparation, while still recognised as important, was not ranked substantially higher than many of the enabling and integrative activities that underpin collaborative research. These results suggest that participants view collaborative science as relying upon a broad ecosystem of contributions distributed across the full lifecycle of an initiative rather than being driven solely by activities occurring closest to publication. Although the survey was not designed to provide statistically representative estimates of the wider Earth science community, it offers valuable insight into how attribution systems are experienced by researchers actively engaged in collaborative initiatives.

Nevertheless, significant limitations emerge when these frameworks are applied to infrastructure-scale synthesis science (**Fig. 1**). First, most authorship systems remain publication-bound[38]. Contributions are evaluated relative to individual papers rather than across the longer lifecycles of collaborative initiatives. This creates a temporal mismatch in which foundational work performed early in a project may become progressively disconnected from later outputs that depend upon it. Second, contributor frameworks tend to privilege task-based contributions over integrative or longitudinal roles[17]. Activities such as governance, strategic coordination, consensus-building and stewardship often involve iterative expert judgement rather than discrete deliverables, making them difficult to encode within existing taxonomies. Third, current systems often struggle to capture the collective and distributed nature of synthesis science. Large initiatives rarely operate through linear workflows. Instead, knowledge production emerges through repeated cycles of discussion, revision and negotiation among multiple contributors with overlapping responsibilities.

The survey results suggest that these concerns are shared across career stages rather than being restricted to a particular cohort of researchers. Experiences of partial or unclear contribution recognition were reported by early-career, mid-career and senior respondents alike (**Fig. 3d**). Although the majority of respondents within each career stage reported clear recognition of their contributions, incomplete recognition was not uncommon, particularly among early-career and mid-career researchers. Importantly, views regarding the adequacy of current authorship frameworks showed no strong career-stage dependency (**Fig. 3e**). Across all career stages, only a minority considered existing frameworks fully adequate, while partial adequacy was the most common response. This pattern suggests that concerns regarding attribution are not simply a consequence of career stage or professional seniority but may reflect broader limitations in how collaborative contributions are recognised. However, leadership and coordination experience were not captured in this survey and may also influence perceptions of attribution independently of career stage.

The relationship between contribution recognition and perceptions of framework adequacy is particularly revealing (**Fig. 3f**). Respondents who reported only partial or unclear recognition of their contributions were more likely to view existing authorship frameworks as inadequate than those who felt their contributions had been clearly recognised. However, even among respondents reporting clear recognition, relatively few considered current frameworks fully adequate, with most selecting only partial adequacy. This finding suggests that dissatisfaction with existing attribution systems cannot be explained solely by individual experiences of recognition. Rather, respondents appear to perceive a broader mismatch between the complexity of collaborative scientific labour and the mechanisms currently used to document and reward it.

These limitations become particularly evident in relation to "invisible labour", work that enables scientific synthesis but remains weakly represented within conventional metrics of productivity and recognition. Community survey responses indicate that contributors regard activities such as workflow and infrastructure development, data generation, coordination and management, synthesis and analysis, and data curation and stewardship as among the most important for the success of collaborative initiatives (**Fig. 4**). Many of these activities underpin collaborative research over extended timescales, yet their contributions may be less readily captured within publication-centred attribution systems than manuscript-focused outputs. Importantly, this is not simply a matter of fairness. Attribution systems shape incentives, institutional priorities, and career trajectories. When critical infrastructure labour remains systematically undervalued, contributors may be discouraged from engaging in the very activities necessary to sustain collaborative science at scale. As collaborative Earth science increasingly depends on long-term stewardship, community governance, and shared scientific infrastructure, the ability of attribution systems to recognise these forms of contribution becomes an issue not only of individual credit but also of the sustainability and resilience of the collaborative enterprise itself.

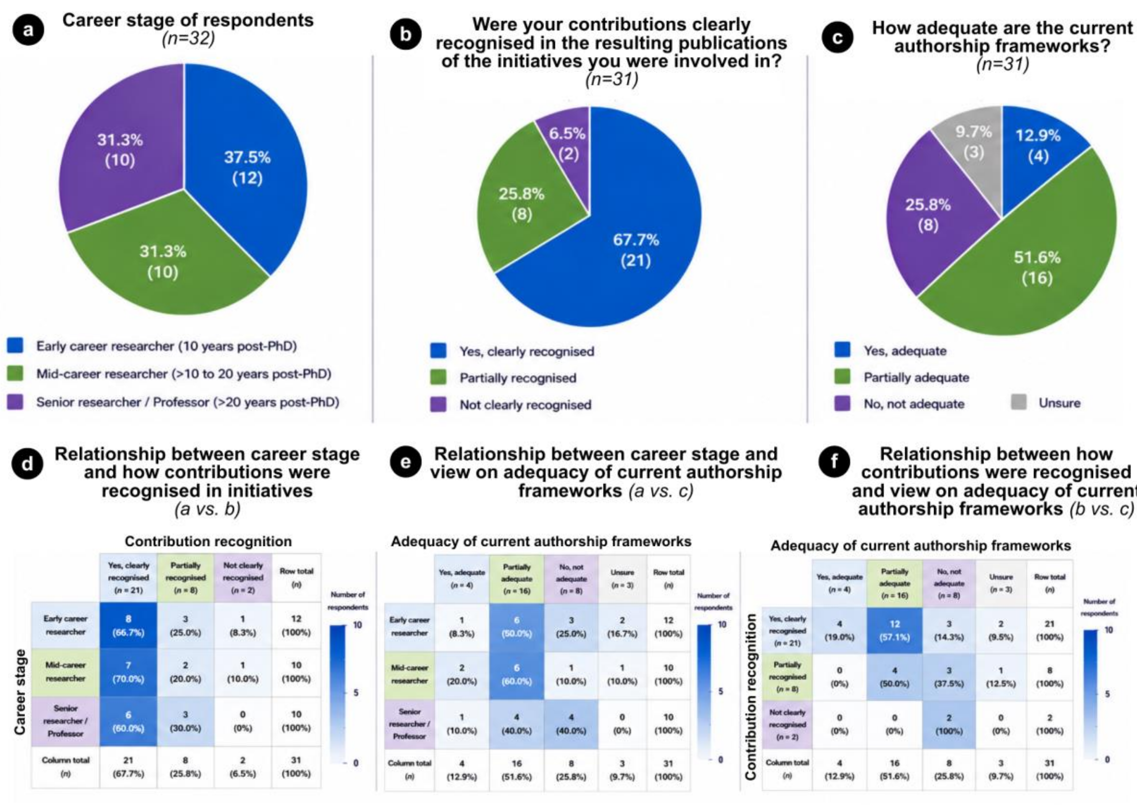

Figure 3: Survey overview of respondent characteristics and perceptions of contribution recognition in collaborative Earth science initiatives: **a)** career stage of respondents; **b)** authorship recognition in existing initiatives; and **c)** adequacy of current authorship framework. Heatmaps show the relationship between **d)** career stage and contribution recognition in existing initiatives; **e)** career stage and adequacy of current authorship frameworks; and **f)** contribution recognition in existing initiatives and adequacy of current authorship frameworks. Total number of respondents, n = 32. *One respondent did not answer questions in **b** and **c** and are excluded from the cross-tabulation. Survey results represent targeted community perspectives and are not intended as statistically representative estimates.

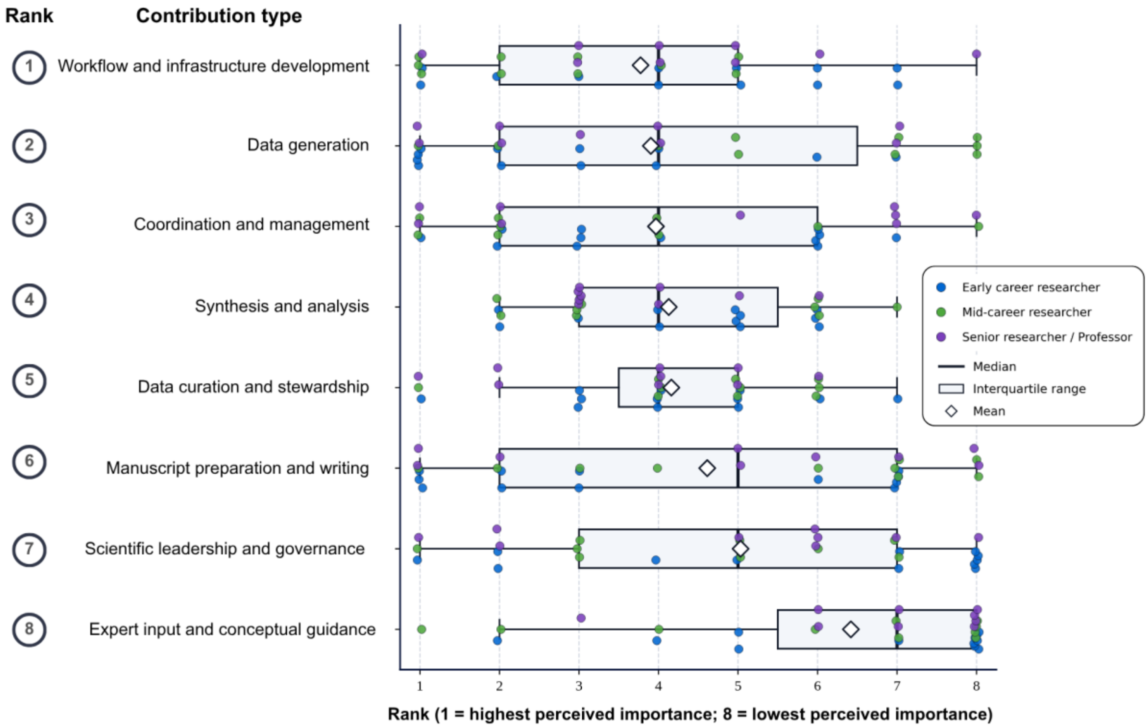

Figure 4: Perceived importance of contribution types in collaborative Earth science initiatives. Horizontal boxplots show the median, interquartile range, and full distribution of rankings for each contribution type. Individual points represent survey responses and are coloured by career stage (early career, mid-career, and senior researchers/professors). Contribution categories are ordered by mean rank from most (1) to least (8) important. Survey responses were obtained from researchers participating in synthesis efforts, modelling initiatives, scientific drilling programmes, and community data infrastructures (n = 31; one respondent did not answer all ranking categories, resulting in n = 30 for some contribution types).

Invisible labour and the problem of visibility

One of the key structural features of collaborative Earth science is that visibility and credit are decoupled not only across types of contribution, but also across the lifecycle of scientific production (**Fig. 5**). While survey results highlight which contributions are perceived as most important by the community (**Fig. 4**), the way these contributions are translated into recognition depends strongly on when they occur within the research process. Activities occurring closer to manuscript production, such as writing, interpretation and direct analysis, are typically more visible within authorship structures than the enabling work performed earlier in the research lifecycle[13] (**Fig. 5a**). As a result, credit becomes concentrated around outputs even when the underlying labour is broadly distributed across time and contributors.

The mismatch between where labour occurs and where recognition is typically captured is a recurring feature of collaborative science (**Fig. 5**). Survey responses suggest that the contributions perceived as most important for sustaining collaborative initiatives are not always those receiving the greatest visibility within conventional attribution systems (**Fig. 4**). Writing and analysis often map directly onto visible authorship positions, whereas stewardship, coordination and governance roles are more likely to appear within acknowledgements, consortium listings or remain entirely invisible. Although these forms of recognition can be scientifically meaningful, they are often less visible within conventional publication-centred attribution and academic evaluation systems. Importantly, these activities are not mutually exclusive. In many collaborative initiatives, the same individuals who provide scientific leadership, governance, coordination, harmonisation and stewardship also play central roles in interpretation, manuscript development and authorship. Importantly, this does not imply that these contributions are scientifically less valuable. Rather, it reflects a structural tendency for publication-centred recognition systems to assign visibility to activities occurring nearest to the final output, while providing fewer mechanisms for recognising the infrastructure and stewardship work that made those outputs possible.

This imbalance has several implications. First, contributors performing foundational work may experience reduced career visibility despite substantial intellectual input. Activities such as establishing community standards, harmonising datasets, developing workflows, maintaining databases, or coordinating working groups can influence dozens of subsequent publications while generating relatively little individually visible credit. These contributions may accumulate recognition through citations, reuse of datasets or software, adoption of community standards, or methodological uptake. However, these forms of recognition are often less directly reflected in authorship positions or in the metrics commonly used to evaluate individual scientific contributions. Second, accountability becomes harder to trace when the decision-making processes underpinning synthesis outputs are poorly documented. Many of the most consequential scientific decisions in collaborative initiatives (e.g. data selection, quality-control procedures, and harmonisation strategies) often emerge through collective discussion and iterative expert judgement rather than through activities that are easily captured within authorship statements. Third, initiatives become vulnerable to burnout and attrition if essential coordination and stewardship work is repeatedly treated as secondary to "visible science"[39]. When contributors perceive that the labour required to sustain collaborative infrastructures carries limited professional recognition, incentives become increasingly misaligned with the long-term needs of the community.

The issue is especially acute for long-term initiatives where contributors may invest years establishing standards, workflows, and harmonisation systems before major synthesis outputs emerge. Although initiative leaders frequently remain closely involved throughout the research lifecycle, collaborative programmes often span many years and multiple phases of scientific development. Leadership, coordination responsibilities and active participation may therefore evolve over time. In some cases, individuals who provide substantial scientific leadership during the formative stages of an initiative may no longer be directly involved when later publications appear. Conversely, contributors responsible for writing and integrating final outputs may receive the most visible forms of credit despite relying heavily on infrastructure developed by others. As collaborative initiatives mature and pass through multiple phases of leadership, participation, and scientific output, the conventional coupling between labour and publication visibility becomes increasingly unstable (**Fig. 5b**). Foundational contributions that shape the trajectory of an initiative may become progressively disconnected from the publications that ultimately emerge from it.

Survey respondents repeatedly emphasised this concern. One participant noted that "foundational work is essential but largely invisible in academic metrics", while another highlighted that "without recognition, people burn out or step away". Although these perspectives emerged from a targeted survey rather than a representative sample of the broader community, they point toward a recurring concern among researchers actively involved in collaborative initiatives. More broadly, they highlight a structural tension between the collaborative realities of infrastructure-scale science and the persistence of output-centred systems of academic evaluation. As Earth system science becomes increasingly dependent on shared infrastructures, long-term stewardship, and distributed expertise, the challenge is not simply recognising individual contributions more fairly but ensuring that the forms of labour required to sustain collaborative science remain visible, valued, and viable over time.

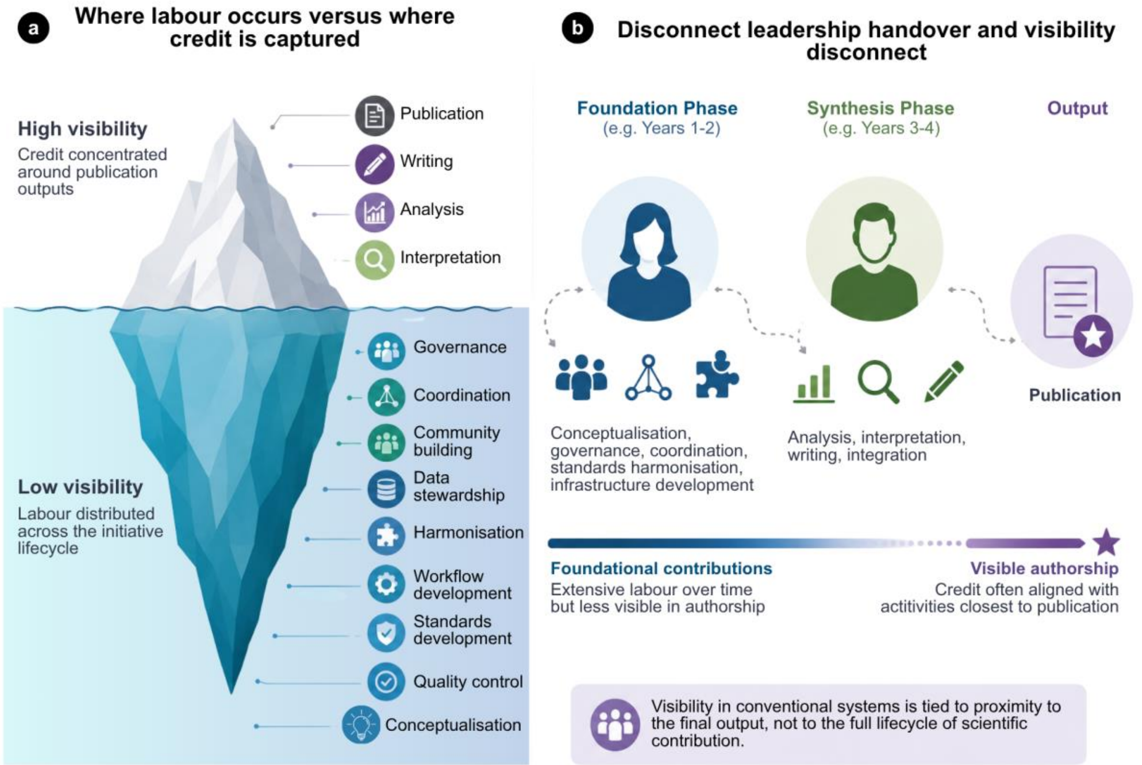

Figure 5: Visibility and recognition across the lifecycle of collaborative science. **a)** conceptual illustration of the mismatch between where labour occurs and where recognition is typically captured in collaborative scientific initiatives. **b)** illustrative example showing how contributions can become disconnected from publication visibility over time.

Emerging community adaptations

Despite these challenges, many collaborative Earth science initiatives have already developed thoughtful and innovative approaches to attribution and recognition. Several initiatives have adopted expanded contribution statements, consortium authorship models[2,24,25] or structured contributor matrices aimed at improving transparency regarding how labour is distributed[13,15,17]. Others have begun developing workflows for contributor tracking[40], persistent identifiers, and versioned infrastructure outputs linked to repositories and community databases[20,37]. These community-led adaptations demonstrate that collaborative initiatives have been actively responding to the evolving challenges of infrastructure-scale science, often developing attribution practices that extend beyond conventional journal requirements. These developments reflect growing recognition that collaborative science depends on a much broader range of activities than can be captured through conventional publication-centred authorship alone.

Survey responses indicated particularly strong support for contributor ledgers, ORCID-linked contribution records and citable infrastructure outputs such as workflow papers, databases, software products, and harmonisation protocols (**Fig. 6a**). Respondents also emphasised the importance of recognising leadership, governance and stewardship roles as intellectually substantive contributions rather than purely administrative activities. Several responses highlighted the need for mechanisms that document contributions continuously throughout the lifespan of an initiative rather than retrospectively at the point of manuscript submission. Many of these recommendations build on practices that are already emerging within collaborative initiatives, including inclusive authorship models, contributor matrices, workshop-based authorship approaches, and tiered recognition systems developed by individual research communities.

Importantly, communities appeared to favour approaches integrated within existing scientific infrastructures rather than entirely new parallel systems. Respondents identified community-developed standards, interoperability with existing workflows, and institutional alignment as key enabling factors for future attribution systems. In many respects, this challenge mirrors the evolution of data stewardship within Earth science. Historically, datasets were often reported only in supplementary materials, accompanied by limited metadata and inconsistent documentation. Over time, community efforts have led to the widespread adoption of FAIR (Findable, Accessible, Interoperable, and Reusable) principles[19], persistent identifiers, standardised metadata, and transparent data provenance. These developments have transformed how data are shared, evaluated, and reused. A similar transition may now be required for contribution recognition, where contributions become discoverable, attributable, and transparently documented throughout the lifecycle of collaborative initiatives rather than only at the point of publication[13,17]. Emerging discussions around complementary frameworks, such as the CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles[41], further highlight the importance of ensuring that systems of attribution remain transparent, inclusive, and responsive to the communities that generate and steward scientific knowledge (**Fig. 6a**).

One particularly promising concept is the use of contribution milestones distributed across different phases of an initiative (**Fig. 6b**). Rather than concentrating recognition solely at the point of publication, milestone-based approaches could provide opportunities to document and acknowledge contributions during standards development, workflow creation, harmonisation activities, governance roles, synthesis efforts, and manuscript preparation. Such frameworks may provide clearer entry and exit points for participation while ensuring that contributors receive appropriate recognition for work performed during earlier phases of a project. This may be especially important in long-term initiatives where contributors move between roles, organisations, or career stages over time.

These emerging adaptations suggest that collaborative science is already evolving toward broader conceptions of contribution. However, the wider adoption and formal recognition of these community-developed practices remain uneven across journals, institutions, funders, and research communities. Many of the innovations described above have emerged organically within individual initiatives in response to the practical realities of collaborative science. Rather than proposing entirely new attribution systems, we propose that these existing community-led approaches provide valuable foundations from which more interoperable, scalable, and broadly recognised frameworks can evolve. Significant challenges remain in developing interoperable, scalable, and widely accepted approaches that can operate across different scientific cultures and collaboration models.

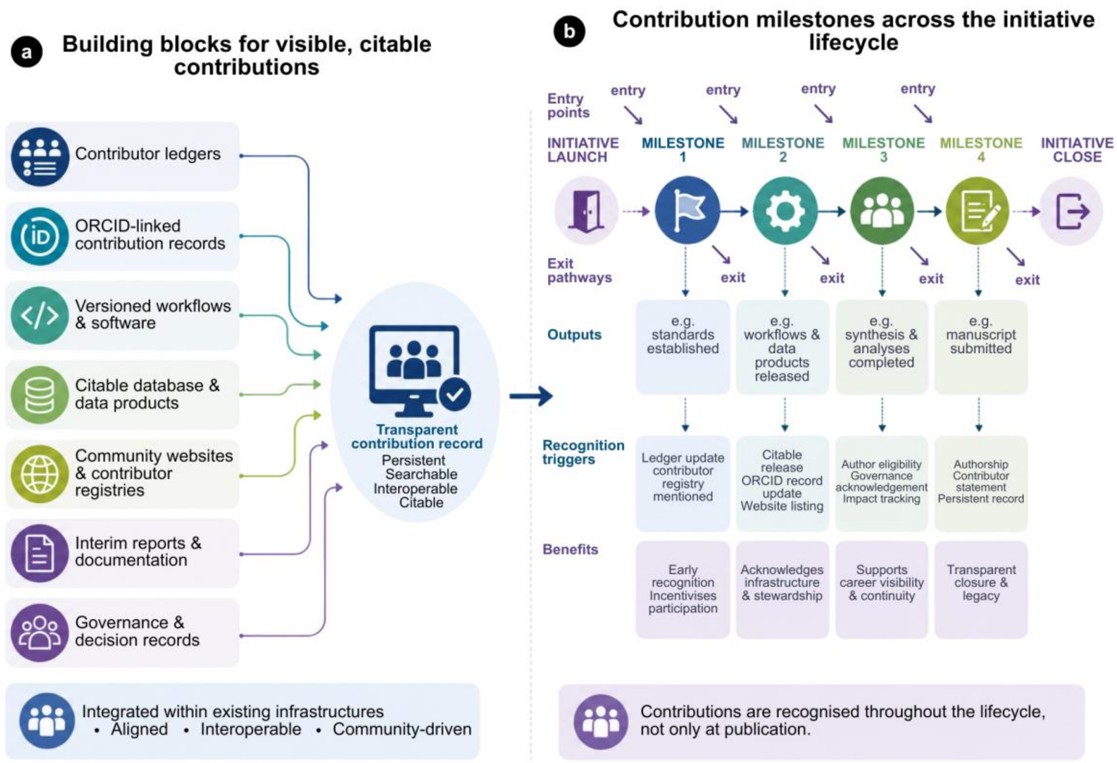

Figure 6: Emerging approaches for recognising contributions in infrastructure-scale Earth science collaborations. **a)** Conceptual framework illustrating complementary mechanisms for improving the transparency, discoverability, and citability of contributions within collaborative scientific initiatives through interoperable contributor records integrated with existing community infrastructures. **b)** Example of a milestone-based contribution framework showing how contributions can be recognised throughout the lifecycle of a collaborative initiative. Entry and exit pathways enable contributors to join and leave at different stages while ensuring that outputs, contribution records, and recognition triggers are documented longitudinally rather than solely at the point of publication.

Toward sustainable infrastructure-scale science

The challenges outlined above are particularly salient for emerging synthesis initiatives designed to function as long-term scientific infrastructure. Increasingly, collaborative Earth science efforts are expected not only to generate scientific outputs, but also to maintain community standards, steward shared resources, coordinate distributed expertise, and provide frameworks that support future generations of research. Such initiatives rely on substantial early-stage, often foundational work, including standard-setting, workflow development, coordination, governance, and scientific leadership, much of which does not immediately translate into visible publication outputs or clear authorship positions (**Figs. 4, 5**). Without clear principles for recognising contributions across phases, early, high-impact work may be under-recognised in later synthesis outputs and within conventional publication-centred attribution systems.

The issue extends beyond questions of individual fairness. Long-term collaborative infrastructures depend upon sustained community participation. When critical infrastructure labour remains poorly recognised, contributors may become reluctant to assume coordination, stewardship, or governance roles despite their scientific importance. Over time, this creates risks for continuity, institutional memory, and community resilience. Conversely, transparent attribution systems can strengthen participation by providing clearer expectations regarding how different forms of contribution will be documented and recognised throughout the lifecycle of an initiative. Agreeing early on role-aware approaches to contribution tracking and authorship can help ensure continuity, fairness, and transparency as initiatives evolve. These considerations are relevant not only for individual initiatives, but also for journals, funders, and international consortia seeking to support sustainable, community-driven science. As collaborative Earth science increasingly operates at infrastructure scale, attribution systems must evolve alongside the scientific structures they are intended to support.

Recommendations

Although no single framework will suit all initiatives, several practical actions emerge from both community responses and experiences within existing collaborative programmes.

Journals

- Require structured contribution transparency statements.
- Expand contributor taxonomies to better capture stewardship, governance, harmonisation, and coordination activities.
- Support evolving consortium authorship models where appropriate.
- Encourage machine-readable contribution metadata and ORCID-linked contribution records.

- Enable citation of infrastructure outputs, including databases, workflows, software, and protocols.

Funders

- Recognise infrastructure labour as a legitimate research output.
- Explicitly value governance, coordination, stewardship, and community-building activities in evaluation criteria.
- Support long-term maintenance and stewardship of synthesis infrastructures.
- Encourage contribution-tracking mechanisms within funded collaborative initiatives.

Consortia and infrastructure-scale initiatives

- Establish attribution frameworks and contribution expectations at the outset of initiatives.
- Maintain contributor ledgers and transparent records of participation.
- Clarify governance structures, leadership responsibilities, and decision-making processes.
- Document scientific arbitration, harmonisation, and consensus-building activities.
- Track contributions longitudinally across the full lifecycle of an initiative.
- Define contribution milestones associated with different phases of participation.
- Create transparent entry and exit pathways for contributors.
- Develop citable outputs beyond journal articles, including databases, workflow papers, protocols, software, and interim reports.
- Maintain contributor registries through project websites and community platforms.
- Periodically review attribution frameworks as initiatives evolve.

Institutions

- Broaden evaluation metrics beyond first- and last-author publications.
- Recognise scientific coordination, governance, stewardship, and infrastructure development as scholarly contributions.
- Incorporate contribution records, infrastructure outputs, and community leadership activities into promotion and assessment processes.
- Encourage use of persistent contribution records linked to researcher profiles.

Researchers

- Maintain clear records of contributions across collaborative initiatives.
- Document contribution roles in narrative CVs, ORCID records, professional profiles, grant applications, and promotion materials, alongside conventional publication metrics.
- Cite and promote infrastructure outputs, including datasets, software, workflows, protocols, standards, and community resources where appropriate.
- Engage with community-developed attribution frameworks and contributor tracking systems to support transparent and longitudinal recognition of collaborative work.

Conclusions

Earth system science increasingly depends on collaborative infrastructures that extend far beyond the boundaries of individual projects and publications. As synthesis initiatives become more mainstream and ever larger in scale, the gap between how scientific labour is performed and how it is recognised has become increasingly apparent. Yet this evolution also presents an opportunity. Just as the Earth science community has successfully adapted its approaches to data stewardship, interoperability, and open science, it now has the opportunity to align systems of attribution and recognition with the realities of modern collaborative research and to future-proof how scientific contribution is defined, recorded, and rewarded. Existing authorship systems remain valuable for ensuring accountability, transparency, and scholarly credit, but they are no longer sufficient on their own to capture the full spectrum of intellectual contributions underpinning infrastructure-scale science. Activities such as stewardship, harmonisation, governance and coordination are not merely supportive functions; they are integral to the production of reliable, reproducible and impactful synthesis science. Recognising these contributions more effectively is therefore not about diminishing the importance of authorship, but about complementing it with approaches that better reflect how collaborative knowledge is generated.

The future sustainability of infrastructure-scale Earth science collaboration will depend not only on computational resources, analytical capabilities, and data generation, but also on whether the human infrastructures that enable synthesis are adequately recognised, supported, and maintained. Building attribution systems that better reflect collaborative reality goes beyond ensuring fairness for individual contributors. It is central to maintaining trust, transparency, accountability, participation, and long-term scientific resilience in the era where many of the most important scientific questions can only be addressed through sustained community effort. Ultimately, the challenge is not whether collaborative science can continue to grow, but whether systems of recognition can evolve alongside it. By developing more transparent, longitudinal, and infrastructure-aware approaches to attribution, the Earth science community has an opportunity to future-proof the collaborative foundations on which much of its scientific progress increasingly depends.

Data availability

Summary survey data, aggregated statistics, and the anonymised responses used to generate the figures and analyses presented in this study are provided as Supplementary Dataset (Survey Data and Aggregated Results). To preserve participant anonymity and confidentiality, individual free-text responses, comments, and raw survey records are not publicly available, as these may contain information that could potentially identify respondents. Additional aggregated information may be made available from the corresponding author upon reasonable request, subject to the protection of participant confidentiality.

Code availability

No code was used in this article.

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