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A multidimensional approach to knowledge coproduction in glaciology

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Abstract

This work presents a reflection on the meaning and significance of knowledge coproduction in the field of glaciology. We start by invoking the paradigm of Structure–Form–Environment Interplay (SFEI) to formulate a generalised definition of glaciology, which highlights the relevance of knowledge coproduction. The adoption of a relational view of glaciological knowledge leads us to identify five core dimensions of knowledge coproduction: purpose, ethics, ambiguity, inclusion/exclusion, and relationships. Based on those dimensions, we delve into the decisive methodological aspects of the coproduction process, namely the definition of its purpose, the identification of participants, the organisation of the process, the recognition of ambiguity in Ways of Knowing (WoKs), and the consideration of ethical implications. In addition to the already known three stages of knowledge coproduction process (codesign, codevelopment, and codelivery), we propose the inclusion of an additional preparation stage, which entails the acknowledgment of the identity and involvement of all human and nonhuman participants, their positionality, and means to ensure their cultural and ontological safety. We reason that knowledge coproduction does not replace the scientific method, but rather complements it, eliciting the possibility to unveil deeper insights that might be difficult to attain through unilateral means.

Introduction

The interdisciplinary nature of glaciology makes it intimately related to the sciences of climate and the environment (Faria, 2009; Laybourn-Parry and others, 2012; Achermann, 2020), sharing with them the qualms and doubts about the potential social and environmental consequences of its research activities. Notwithstanding, drawing from its (geo-)physical roots, glaciological research has traditionally been performed with a positivistic perspective on exploration, deduction, and data collection, which identified the scientific method as the sole legitimate means of knowledge validation. While such an approach is undeniably powerful, it has recently been criticised for not recognising the fact that earth-science knowledge can no longer be regarded as just a neutral set of formal and systematic statements, such as hard and quantitative data (Sörlin, 2009; Carey and others, 2016; Tadaki, 2017; Burton, 2022). Rather, it has evolved to be also *relational* (Bouwen, 1998; Bouwen and Taillieu, 2004; Brugnach and Ingram, 2017), in the sense that its production and significance depend on *who* is included in the problem-understanding process, *how* those included relate to each other to define the problem, and *what* type of knowledge is needed.

The relational aspects of knowledge just mentioned give rise to the concept of *Ways of Knowing* (WoKs), which is the process through which a problem or question is perceived, defined, assessed, and addressed (Feldman and others, 2006; Lejano and Ingram, 2009). The collective-interactive creation of knowledge by means of inclusion (*who*), relation (*how*), and validation (*what*) of diverse WoKs constitutes what is known as the process of *knowledge coproduction* (Bouwen and Taillieu, 2004; Brugnach and Ingram, 2017).

The recognition that modern glaciological knowledge consists of both systematic (e.g. data-driven) and relational aspects, suggests that research and problem-solving in such contexts generally involves many WoKs, wherein knowing requires an understanding that is not only rational and cognitive, but also intersubjective and relational (Brugnach, 2017). Evidently, the degree of WoKs diversity depends on the problem at hand, ranging from bare interdisciplinarity (e.g. first-principles study of proton disorder) to complex relational processes (e.g. glacier hydrology in populated areas). In general, however, the relational aspects of glaciological research are often underestimated. For instance, as will be discussed in more detail in the next sections, cryospheric research intrinsically has a strong relational component, due to its connections with the climate system, the environment, and human communities. Glaciers are more than just big masses of frozen water, they are perceived through an assemblage of relations that make them knowable and meaningful (de Landa, 2006). Nevertheless, many glaciologists still fail to recognise the relational component of their research, particularly in the most remote areas (e.g. Antarctica), with the misled argument that knowledge coproduction cannot transpire in an environment devoid of human communities and infrastructures.

In this work, we defend the thesis that a strictly detached approach to glaciological research may sometimes be *incomplete*, as it disregards the modern requirements of sustainable and actionable science. Scientific knowledge is deeply connected to societal influences and plays a fundamental role in shaping social order. As Jasanoff (2004) argues, science and society are mutually constitutive: the creation and validation of scientific knowledge shape social structures, norms, and values, while the social and political context in which science is produced influences what kinds of knowledge are generated and accepted.

A more complete approach to glaciology shall integrate factual-scientific knowledge with other WoKs, through a process of coproduction that attends to plural perspectives practices, interests and aims while recognising the uncertainties, ambiguities, and contradictions involved in the process (Brugnach and others, 2017; Lepenies and others, 2018; Chambers and others, 2021). When properly performed, knowledge coproduction can provide a venue to gain a more democratic and comprehensive understanding of the cryosphere, and its relationship with people and the environment, and so serve to better achieve purposeful collective action.

Knowledge coproduction in glaciology

Defining the realm of glaciology is not a trivial task. Its interdisciplinary nature and ramifications into the physical, formal, and applied sciences, life and social sciences, and the humanities, make its boundaries diffuse (Faria, 2023). The situation is aggravated by the persistent, popular misconception that glaciology were derived from the word 'glacier', implying that it would mean merely 'the study of glaciers'. As pointed out by Seligman (1961), the word 'glaciology' is actually derived from the Latin '*glacies*', which means ice, and it '… *has always been intended to cover every form of ice*.'

Today, strong interactions and teleconnections between the cryosphere and various biotic and abiotic components of the earth system have been uncovered, revealing the transmission of signals and disturbances through the climate system, not only through physical and chemical processes but also through biological and societal pathways (Bravo and Rees, 2006; Hovelsrud and others, 2011; Laybourn-Parry and others, 2012; Bravo, 2017). A simple way to summarise all those interactions and connections is through the paradigm of Structure–Form–Environment Interplay (SFEI; Faria and others, 2009, 2018) illustrated in Figure 1. The SFEI paradigm can be applied to a particular research topic or to glaciology as a whole. In the latter case, 'Structure' refers to the substance, ice of all kinds (i.e. snow, firn, ice, permafrost, etc.); 'Form' stands for all fashions of glaciological bodies and systems, either of natural origin (e.g. glaciers, ice sheets, sea-ice fields) or artificial (cold chains, freezing systems, etc.); 'Environment' denotes all types of surrounding features, like for example, natural and human systems.

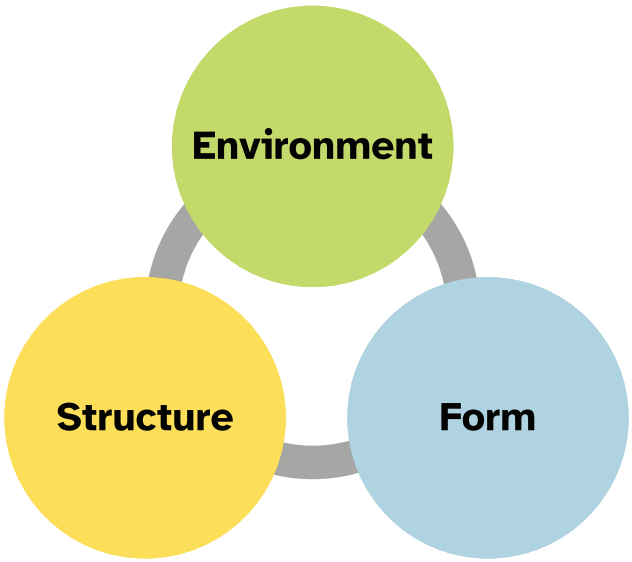

Figure 1. Schematic representation of the Structure–Form–Environment Interplay (SFEI). The environment acts on form and structure; changes in form affect structure and environment; the structure influences form and environment.

The SFEI paradigm provides a logical generalisation of Seligman's (1961) definition of glaciology as *the study of all kinds of ice* (Structure) *in any fashion* (Form) *and considering all effects and consequences* (Environment). It implies that a complete glaciological study entails coproduction, not only on the scientific level through an interdisciplinary approach (intrinsic to glaciology as a scientific discipline), but also through the integration of techno-scientific knowledge with other WoKs inherent to the Environment.

Such a generalisation of the definition of glaciology is essential to consolidate its *relational nature* over multiple scales, contexts, disciplines, and WoKs. A look at the glaciological literature reveals that the relational nature of glaciology harbours a huge research potential that has barely been explored yet. Indeed, most approaches to knowledge coproduction to date have tended to be topical and specialised, short-termed, or geographically localised:

- In the context of *high mountains and the Arctic*, several studies have reviewed and examined the varying degrees of local participation and coproduction, and further developed frameworks to assist researchers, policymakers, and communities in moving towards the goal of coproduction (Robards and others, 2018; Thompson and others, 2020; Davis and others, 2021; Yua and others, 2022). They concluded that coproduction attempts have often been limited to participation in data collection, thus being more consultative than collaborative. Failed attempts are usually characterised by merely adhering to protocols and funding criteria, resulting in tokenism (Davis and others, 2021; Yua and others, 2022). Researchers rarely indicate how the local communities were involved in the research stages, including research planning, implementation, and evaluation of the research activities, as well as their share in power dynamics and governance. Several case studies of knowledge coproduction in Alaska have attributed their success to iterative and cyclic processes to define and resolve problems on a small location-based scale, and then eventually evolved to larger projects (Robards and others, 2018). Another key element that was crucial for inclusive, equitable, and sustainable coproduction was placing emphasis on enacting Indigenous governance and sovereignty and ensuring continued access to culturally important resources (Thompson and others, 2020; Hauser and others, 2021).
- In the context of *Antarctica and other global commons* (i.e. Antarctica, the high oceans, the atmosphere, and outer space), the coproduction of glaciological and environmental knowledge has been significantly shaped through boundary organisations, which have played a decisive role in brokering knowledge between producers and users, including continued observation, deliberation and negotiation, which help develop a lasting trust and relationship among all parties (Elzinga, 1993; Dodds and others, 2017; López-Martínez, 2020). Furthermore, boundary organisations may also act as the very agents of coproduction, answering for the protection of such remote regions

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(Kennicutt and others, 2014; Hughes and others, 2018). That kind of coproduction is becoming increasingly important for Antarctic research, as the human activities in the southernmost continent (including research, tourism, and fishing) have grown dramatically in recent years, with powerful nations strategically positioning themselves to exploit weaknesses in the current Antarctic Treaty System[1] and the potential revision of several of its critical elements by 2048 (McGee and Liu, 2019; World Ocean Review, 2019, and references therein[2]).

The relational nature of glaciology unveils many direct and indirect interconnections, interactions, functions and consequences involving the cryosphere and its research. In particular, it invites glaciologists to reflect on their own research practices, roles and responsibilities, through the interconnections of glaciology with the social sciences and humanities on topics about, for example, research responsibility, sustainability, inclusiveness, and knowledge coproduction[3] (Bravo, 2009; Sörlin, 2009; Carey and others, 2016; Dodds and others, 2017; Radin and Kowal, 2017; de Pomereu, 2019; Burton, 2022; Carey and Moulton, 2023; Robel and others, 2024). Such studies shed light on the political, cultural, artistic, historical, philosophical, moral, and legal aspects of glaciological practices and glaciology itself. Accordingly, they deal with many questions related to coproduction in glaciology, like: Who responds for Antarctica? How to diagnose glaciological neo-colonialism? Is it legitimate to integrate glaciological local knowledge? Which measures can promote sustainability and inclusiveness in glaciological research? Finding answers to those and similar questions entails relating to multiple actors holding different WoKs. Some of them may have developed knowledge systems that, being different from the natural sciences, hold important practical or traditional wisdom embedding the experience of a long-lived connection to ice or related issues.

Coproduction of knowledge occurs by integrating all those WoKs into meaningful solutions that are useful, fair, and consensual. The integration is not straightforward, however, because the relational processes bear unavoidable uncertainties, ambiguities, and contradictions that must be identified and managed. In the next sections, we explore key concepts of knowledge coproduction, to gain deeper insight into the implications, drawbacks, and benefits associated with the generation of novel forms of glaciological knowledge through coproduction processes.

Dimensions of knowledge coproduction

The notion of knowledge coproduction is underpinned by the need to better link science and society in addressing issues or problems of common concern, producing blended forms of knowledge that are pertinent to the interests, values, and needs of those whose stakes are at play (Lepenies and others, 2018; Beck and others, 2022; Büttner and others, 2023). While there are many ways in which the coproduction of knowledge has been conceptualised and practised (relevant reviews are Bremer and Meisch, 2017; Brugnach, 2017; Lepenies and others, 2018; Miller and Wyborn, 2020), generally it makes reference to the process of generating actionable knowledge forms by combining a plurality of knowledge sources and types (e.g. scientific, expert, local knowledge). Such a process is not meant to be limited to an intellectual exchange or interdisciplinary integration of neutral and objective scientific knowledge. Instead, it is intended as a space for the development of novel, relational forms of knowledge, research, and action that, without excluding objective science, permit connecting different existing WoKs and bodies of expertise and skills.

In practice, knowledge coproduction can be understood as an iterative process of the coordinated action of diverse actors (e.g. stakeholders, shareholders) who engage in some form of collaboration to create knowledge capable of addressing common collective problems (Brugnach and Özerol, 2019; Bandola-Gill and others, 2022). A process of mutual understanding that is carried out via dynamic interactions among knowledge holders, who while working toward common objectives, exchange what they know and what they need through discourse and communication. Ample evidence suggests that through these collaborative processes, new ways of comprehending can be developed, broadening the boundaries of substantive knowledge, while at the same time providing knowledge that is more suited to actors' requirements and hence more likely to be employed (Lemos and others, 2018; Chambers and others, 2021; Howarth and others, 2022).

When adopting a relational view of knowledge, there is no fixed recipe for how to carry out processes of knowledge coproduction. These are processes that are case-specific and contextually defined, and as such they can rarely be standardised. However, a growing body of research in coproduction indicates that coproduction must operate at two levels:

(1) *Substantive:* referring to the content that is being created for the purpose sought.
(2) *Procedural:* referring to the rules and organisation underlying the process of knowledge creation that bring about substance; and in doing so, to pay close attention to who gets to participate, under which conditions, towards what end, what relational practices support actors´ interactions, how differences and controversies are resolved (Caniglia and others, 2023).

Next, we will look in more detail at the five core dimensions of knowledge coproduction (Fig. 2), how these processes can be

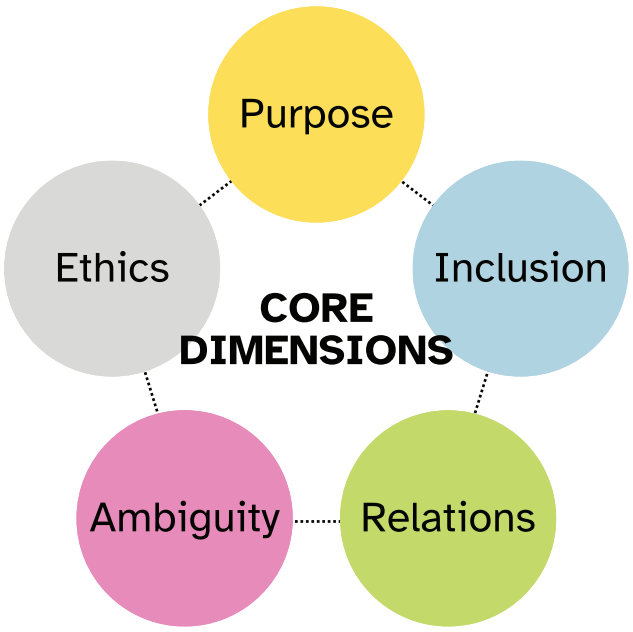

Figure 2. Core dimensions of knowledge coproduction.

[1]Secretariat of the Antarctic Treaty; url: https://www.ats.aq.

[2]See also Hook L and Mander B (2018) The fight to own Antarctica. Financial Times, 24 May 2018. Retrieved on 2 April 2024; url: https://www.ft.com/content/2fab8e58-59b4-11e8-b8b2-d6ceb45fa9d0.

[3]See also Craciun A and 9 others (2022) *Icy Humanities: A Collaborative Symposium.* Online workshop hosted on 5 April 2022 by The Frederick S. Pardee Center for the Study of the Longer-Range Future at Boston University's Pardee School of Global Studies and the Scott Polar Research Institute at the University of Cambridge; url: https://youtu.be/vJhjUWTkchA.

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applied, and how they may serve to advance what is known about ice.

Knowledge coproduction is a process with a purpose

Coproduction processes can encompass diverse meanings and ends, underlying motives that are numerous and diverse (Lepenies and others, 2018; Norström and others, 2020; Maas and others, 2022; Honeybun-Arnolda and others, 2024). The coproduction of public services, the codevelopment of knowledge to support decision-making, or the cocreation of solutions to common challenges, are a few common examples. The purpose of a coproduction process is what determines who gets to participate, what resources are needed, and how a process is organised. In glaciology, some frequent purposes of coproduction are the development of adaptation strategies for local communities, protection against cryospheric hazards, support of decision-making for governance, and improvement of sustainable and responsible research (Bravo, 2006; Hughes and others, 2018; Chown and Brooks, 2019; Abdel-Fattah and others, 2021).

Coproduction of adaptation strategies and protection against cryospheric hazards refers to the processes that are carried out at a regional scale with the objective of developing, jointly with various actors, forms of adaptation in the context of hazards related to cryospheric climate change. In mountain regions, not only are the cryospheric components such as ice, snow, and permafrost at direct risk of melting and disappearing (IPCC, 2019) but also the local communities who are dependent on these elements. While the vulnerability of these communities varies geographically and to different degrees, effects on water supply and economic dependence seem to be of particular importance. High-mountain communities and downstream users worldwide rely on the seasonal supply of water from melting snow and glaciers, and the impacts of climate change on these elements will consequently have effects on the water availability for drinking, irrigation, and hydroelectricity (Immerzeel and others, 2020; Lutz and others, 2022). Risks of glacier lake outburst floods (GLOFs) are also increasing (Harrison and others, 2018; Bazai and others, 2021). In the Alps and other European high mountains, the impacts of decreasing snow cover, melting glaciers, and increased risk of ice and rock avalanches are observed in the tourism sectors that depend heavily on winter and mountaineering activities (Bruley and others, 2021; Salim and others, 2021). With rapid changes occurring in the cryosphere, ecosystem services across the world are inevitably affected, which makes it imperative for different actors to create and implement effective adaptation plans (Moors and others, 2011; Huggel and others, 2020; Drenkhan and others, 2023).

The objective of improving decision support for governance and for sustainable and responsible research is twofold: (i) to minimise the impacts of glaciological research activities upon natural environments and local communities (Hughes and others, 2018; Kettle and others, 2019), and (ii) to adapt the existing ecosystem and climate services surrounding glaciology to the specific needs and interests of local users (Bravo, 2006; Abdel-Fattah and others, 2021). Decision support tools encompass resources that help support decisions at different scales including information gathering, data analysis and modelling, and decision implementation (Bhargava and others, 2007). Such tools have historically utilised technological and analytical approaches but equally important are social communication, local observations, and voices that provide information beyond data and numbers (Cruikshank, 2005; Bravo, 2009; Sandré and others, 2024).

For example, in the *Alaskan Arctic*, the development of collective decision support tools has been particularly important as vast resources and ecosystem services related to sea ice and wildlife are shared and used by many actors including traditional hunters, local communities, scientists, and offshore industry operators. Local communities and subsistence hunters have generations of experience and knowledge on their local conditions and environment that are useful for purposes such as understanding sea-ice safety for travel and expeditions (Albert, 2000; Mahoney and others, 2007; Kettle and others, 2019), conservation of wildlife and protection of their habitat, risk, and benefit assessment for consumption of subsistence food (Moses and others, 2009; Babu, 2023), and minimising offshore oil and gas as well as shipping traffic (Davis and others, 2021).

Decision support to minimise the impacts of glaciological research activities is also crucial for inhabited regions. For instance, *Antarctica* is identified by international law as one of the four *global commons* (together with the High Seas, the Atmosphere, and Outer Space), defined as those parts of the planet that fall outside national jurisdictions and to which all nations have access (UNTT, 2013; Dodds and others, 2017). As such, the Antarctic environment and its resources are protected by the principle of the common heritage of humankind (Joyner, 1986), which guides also the planning of Antarctic research and governance (see e.g. the scientific advice to the Antarctic Treaty System and the codes of conduct for scientists working in Antarctica provided by the Scientific Committee on Antarctic Research, SCAR: https://www.scar.org/).

Knowledge coproduction includes and excludes

The coproduction of knowledge involves creative processes that notably differ from the traditional production of scientific knowledge through the scientific method. Instead of having a main knowledge holder (i.e. a scientist) observing and describing an external reality, during a coproduction process, there are networks of actors holding diverse forms of knowledge, which come together to create yet new blended knowledge forms collectively. These actors define the issues of concern, determine what needs to be known and done to address them and identify the type of knowledge that needs to be developed. Attention should be given to the fact that the inclusion of certain actors inherently determines who is excluded.

In a coproduction process, actors are knowledge holders who can be involved in several different ways (Davis and others, 2021). Considering involvement from the perspective of power, Arnstein (1969) distinguished between different roles, from non-participation (manipulation, treatment), tokenism (informing, consultation, placation), and citizen control as inclusive forms of self-mobilisation and auto-determination. Being aware of the type of actor engagement helps align individual and collective expectations regarding roles and responsibilities in the creation of the new knowledge, making the process more transparent and also asserting that the people who need to be involved are actually involved, so as to mobilise the knowledge that is needed.

In glaciology, the question of who produces glaciological knowledge, and how such knowledge is used or shared is not usually emphasised. Systems of domination and structures of power and patriarchy have long fed the production of glaciological knowledge (Bravo and Triscott, 2011; Carey and Moulton, 2023; Robel and others, 2024) and this has set the standard where the 'who' has predominantly been the Western scientists. Other forms of cryospheric knowledge, such as folk and grass-roots glaciology, which have been produced at different times and places by diverse peoples, cultures, and social groups (Cruikshank, 2005; Carey and others, 2016; Munir and others, 2021), have remained marginalised. Here, we suggest that knowledge coproduction can provide an opportunity to decentralise this 'who', amplifying the voices and narratives of those whose glaciological knowledge has been systematically dismissed.

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Knowledge coproduction builds on relationships

Coproduction processes that support the creation of new knowledge go in tandem with developing high-quality relationships among actors, based on mutual understanding and trust (Brugnach, 2017; Fleming and others, 2023). That allows advocates for supportive dialogical settings, where mutual listening, debate, learning, and negotiation are encouraged, to communicate their expectations and presumptions. Through these exchanges, they collaborate to generate new blended knowledge forms. It also implies paying close attention to the interaction among knowledge holders, and the relationships of production and power underlying the exchange of knowledge among them.

Coproduction procedures must pay special attention to 'what is going on' while the actors are interacting. It is critical to take into account not only who is engaging and who is missing, but also what happens when different actors interact: how people communicate, what is said, and what is not said. It is conceivable for powerful individuals to impose their opinions in order to further their own agendas (Zingraff-Hamed and others, 2020). Well-performed coproduction processes must consider empowerment programs and operational and structural support instruments (such as legal aid, information access, and capacity building) that restore the balance of power among participants (Gerlak and others, 2023). They also call for a continuing review of the participation rules (Brugnach and others, 2017). In short, setting a coproduction process to work demands much more than merely bringing knowledge holders to a table: it requires the capacity for dialogue among knowledge holders, even when power asymmetries, identity issues, differential access, or control over resources or information is at play.

At a global scale, the IPCC provides a notable example. Until the IPCC's Fourth Assessment Report (AR4), Indigenous Peoples were largely overlooked as holders of valid knowledge, and their contributions were neglected (Ford and others, 2016; Brugnach and others, 2017; Mahony and Hulme, 2018). Since then, the IPCC has made significant efforts to include Indigenous knowledge, however effectively integrating nonscientific perspectives with scientific literature remains a significant challenge (Chen and others, 2021). Critics argue that the IPCC engagement with Indigenous knowledge frequently is superficial and tokenistic, prioritising scientific epistemologies, thereby perpetuating power dynamics that marginalise and sideline nonscientific knowledge forms, particularly those rooted in Indigenous traditions (Hernandez and others, 2022; Carmona and others, 2023; Rashidi, 2024). These dynamics are further exacerbated by institutional structures, which often exclude Indigenous Peoples from meaningful participation (Asayama and others, 2023).

In knowledge coproduction ambiguity is unavoidable

Often hidden within assumptions, the coproduction of knowledge among multiple holders also entails handling ambiguity. Ambiguity arises when diverse WoKs are brought together, leading to confusion and differing interpretations within a group (Brugnach and Ingram, 2012). It reflects the differences in understanding among knowledge holders regarding a particular situation. Inherent in any coproduction process that involves diverse actor groups, ambiguity highlights that WoKs may not always align.

Ambiguity can manifest in various ways, pointing out discrepancies that may be substantive (such as differing views on the significance of a melting glacier), procedural (involving rules, formal agreements, regulations, or laws, such as measures to mitigate landslide, avalanche, and glacial-flooding risks), or process-related (concerning informal relationships, interactions, and participation, such as the roles played by scientists, boundary organisations, and local actors).

While ambiguity can be a valuable source of creativity and innovation, it can also lead to contradictions and even conflicts among knowledge holders, hindering the group's ability to work collaboratively toward a common goal. These differences may create confusion about the primary issues of concern, the relevant sources of knowledge, how to integrate different WoKs, or what actions need to be taken. In the process of coproducing knowledge, it is crucial to recognise and address these differences in a way that constructively harnesses the diversity of WoKs rather than diminishing it. In such contexts, dialogical forms of coproduction are particularly effective (see Brugnach and others, 2011, for various strategies to navigate ambiguity).

When working in polar or high-mountain regions, ambiguity becomes also an inevitable consequence of knowledge coproduction between glaciologists and local communities, as those actors hold different WoKs, values, practices, and systems. As a result, discrepancies arise in the framing of the glaciological issue and its relevant solution, be it a loss of glacier mass from a geophysical perspective or the loss of a cultural monument and water resource through the eyes of local communities (Cruikshank, 2005; Bravo, 2009; Carey and Moulton, 2023). This ambiguity then has implications for the management, conservation, and adaptation plans, and often results in disagreements, misalignments, and tensions among people (Brugnach, 2017).

Exemplary instances of ambiguities arise when the geophysical view of glaciologists is confronted with the cultural and symbolic values of glaciers for the local communities living near them (Orlove and others, 2008). In the Canadian Arctic, for instance, Cruikshank (2005) reports local narratives of sentient glaciers that become offended by the smells of cooking with grease, sometimes reacting with great danger, for example, through glacier surges. In the Karakoram, local understanding assigns genders to the glaciers, which can be combined through the Indigenous practice of glacier grafting to generate new ice (Gioli and others, 2014; Munir and others, 2021). While climate change projections warn of drastic glacier retreats globally (IPCC, 2019), the current climatic anomaly in the Karakoram results in relative glacier stability (Hewitt, 2005; Farinotti and others, 2020), which may spark peculiar expectations of glacier and hydrological security among the local people. Here, acknowledging and addressing ambiguities in knowledge and future climate projections become key issues in the adaptation to climate change. On the one hand, because their absence would rather entail that other forms of knowledge outside the dominant one have been dismissed or invalidated. On the other hand, because local knowledge forms can offer alternative venues for adaptation that are not foreseen with science alone.

Knowledge coproduction demands clear ethical boundaries

Creating blended knowledge that goes beyond scientific understanding and includes different WoKs raises ethical implications regarding the participatory processes underlying knowledge development and its substantial output, bringing up fundamental questions about property rights, knowledge sharing, and use. Several authors have argued that knowledge coproduction between scientific and nonscientific actors (e.g. local communities) can lead to the emergence of a participation paradox (Craps and others, 2004; Quaghebeur and others, 2004); where local knowledge holders may find themselves excluded by the knowledge, structures, and procedures that are meant to involve them, reinforcing even more the relationships of power and the legitimisation of scientific knowledge (Brugnach and others, 2017). Notably, there are issues concerning:

(1) *Self-determination:* It raises questions regarding the process underlying coproduction, if, for example, it is voluntary and

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informed, and regarding the influence or authority granted to the nonscientific actors. In knowledge coproduction and collaborative partnership among different knowledge holders, there should be a consensual agreement on their 'knowledge sharing process'. This requires 'cultural safety', an inclusive environment fostering a trusting and reciprocal working relationship with individuals from diverse cultural backgrounds (Bourassa and others, 2020). When knowledge is sacred, this process becomes increasingly important as it is not necessarily sharable or accessible without special rituals or practices (Fung, 2006; Brugnach and others, 2017).

(2) *Property rights and transparency:* Taking into account property rights and transparency involves examining the legitimacy of the representation of knowledge holders, questioning who is being credited for the coproduced knowledge and if the use of local knowledge forms is used with the proper consent of its legitimate owners. In climate-change-related projects, it is not uncommon a lack of transparency and accountability, and as a result, elite groups, including scientists, are able to capture the benefits, sometimes even to the prejudice of Indigenous communities (Turner and Clifton, 2009; Brugnach and others, 2017; Klenk and others, 2017; Jull and others, 2018).

(3) *Knowledge appropriation:* Issues of appropriation involve assessing whether nonscientific knowledge is appreciated in its entirely or fragmented into data to conform to the standards of Western science. It is important that the coproduction process does not discount and local and indigenous knowledge by treating them merely as an extractive source available for scientific research. The appropriation of local knowledge systems out of their original context to fit into the epistemological and ontological framework of Western science not only marginalises local WoKs, but also breaks the ties that bind local knowledge to their local interests, governance, and social practices (Smith and Sharp, 2012; Latulippe and Klenk, 2020).

In sum, in glaciology, as in any other complex multidisciplinary field, knowledge coproduction can be viewed as a process that connects different WoKs by bringing together the expertise and skills of a wide range of actors in ways that are fair and inclusive of their needs and concerns. Its essence lies in creating opportunities for the development of novel forms of knowledge, study, and action that are capable of delving into the knowledge and wisdom of people and places (Muhl and others, 2023). It is a process that involves working together with humans, and also nonhumans-others, towards a common end, where science, even though essential, is not privileged as the sole legitimate way of knowing.

The knows and hows of knowledge coproduction

What do we coproduce? How do we do it? And what is our role in that process? The concepts outlined above indicate that the paradigm of knowledge coproduction heralds a transformative approach to building new knowledge in the field of glaciology. Applying the theory demands the re-evaluation of traditional researcher roles and the development of interpersonal competencies, as the knowledge creation derives from complex social interactions that are specific to a particular situation. Within these synergistic interactions, the participants make sense of reality and negotiate its meaning to jointly define and solve a problem (Brugnach and Ingram, 2012). Hence, the development of actionable knowledge necessitates concentrated efforts among individuals, groups, or organisations.

Several authors have argued that the coproduction process entails three different stages: codesign, codevelopment, and codelivery (Wyborn and others, 2019; Fleming and others, 2023). Here we suggest an additional *preparation stage* (see Fig. 3), as a precursor of any collaborative process of coproduction.

(1) *The preparation stage* includes the identification and involvement of relevant participants and their positionality, as well as the securing of cultural safety (Bourassa and others, 2020; Holmes, 2020). See Ford and others (2019) for an example that integrates Indigenous knowledge with science to quantify the impact of climate change on trail access in the Inuit Nunangat (Canada), where preparatory co-production plays a crucial role in shaping the development and outcomes of a modelling framework.

(2) *The codesign stage* consists of identifying joint objectives, creating a common ground and equifinal problem definitions (Gray, 1989), and designing the processes and procedures that are used to derive new knowledge. If the design is responsive to feedback, these activities may continue beyond the initial stage, fostering equitable partnerships.

(3) *The codevelopment stage* encompasses the management of the actual coproduction of knowledge, including the logistics, relationships, and individual capacities. To address issues of scale and power, the researcher has to switch between being a reflective scientist, mediator, and facilitator. Furthermore, it demands the ability to embrace ambiguity and eventual conflicts that arise when integrating different perspectives with, for instance, dialogue learning and negotiations (Brugnach and Ingram, 2012; Chambers and others, 2021; McCabe and others, 2023).

(4) *The codelivery stage* consists of jointly delivering the completed project and sustaining the coproduction. One measure is ensuring the application and ongoing maintenance of the new knowledge within the community, industry, government, etc.

During the proposed four-stage cyclic process, it is crucial to acknowledge that pertinent local actors may encounter barriers preventing their engagement, for example, due to a lack of willingness or financial constraints, necessitating situation-specific strategies (Wyborn and others, 2019). Hence, our proposed four-stage process of knowledge coproduction differs in many ways from the scientific method: it does not represent a replacement for the scientific method, but rather a complementary approach, which demands the application and development of new skills. This approach aligns with the call for scientists to engage in more meaningful and respectful collaborations with Indigenous communities, as highlighted by Wong and others (2020) in their ten calls to action towards reconciliation.

Taking on the social and environmental responsibility of the new knowledge creation means emphasising inter- and transdisciplinary collaborations, which go beyond science to include multiple knowledge forms and engage nonscientific actors. Thus, coproduction processes require a high level of reflexivity and trust among all actors. Moreover, implementing those processes demands people skills like justice, care, humility, courage, cultural competency, and sensitivity to carefully account for all actors involved or affected, including conflict resolution skills (Caniglia and others, 2023; David-Chavez and others, 2024). The complexity added by the collaborative process of knowledge coproduction is likely to be offset by the unveiling of deeper insights that might be difficult to attain through unilateral means (Fox and others, 2020).

Conclusion

> *Nor would it concern them* [the indigenous peoples who contributed to the early Arctic exploration] *for an instant that their names should be left off*

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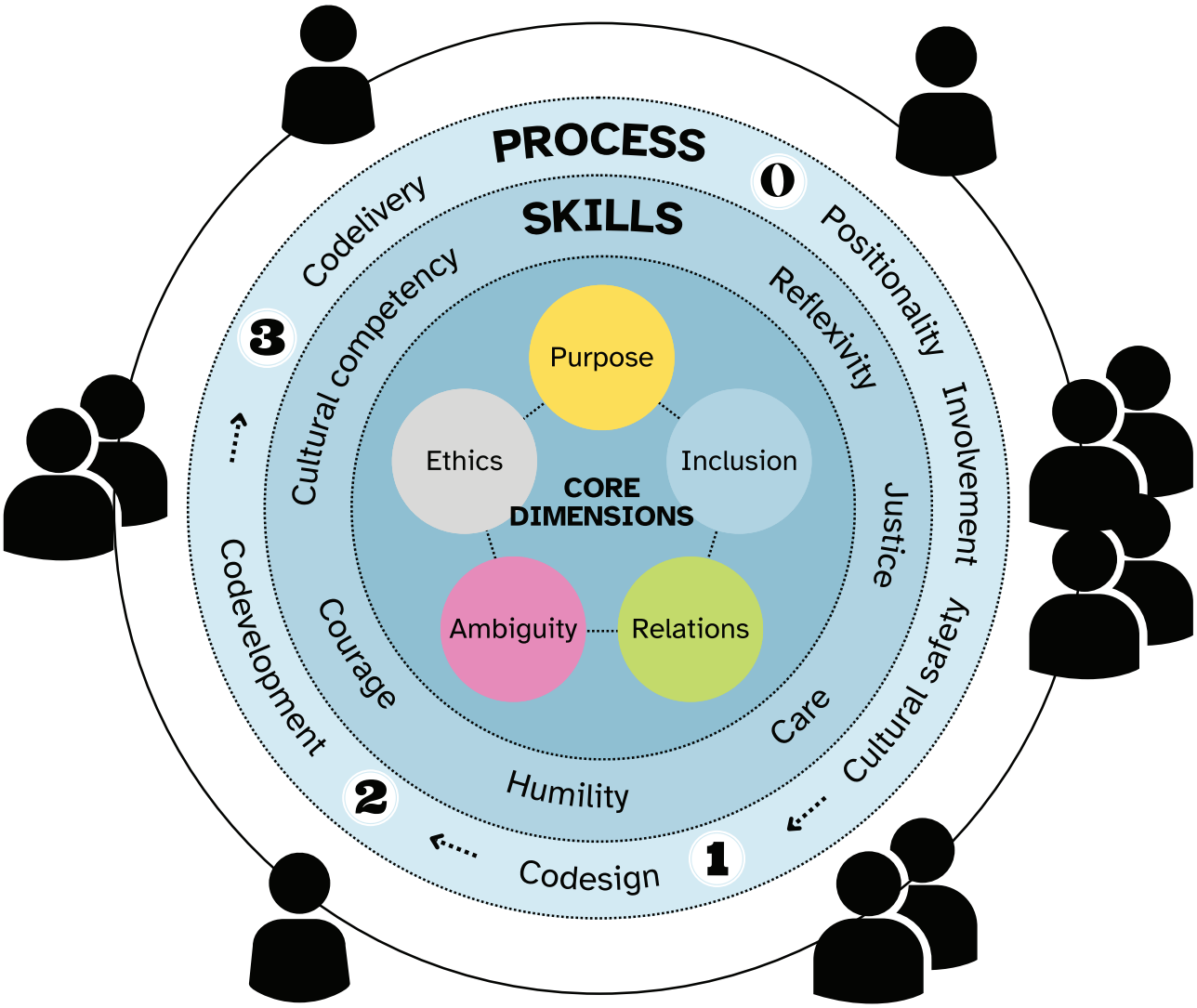

Figure 3. Visualisation of knowledge coproduction in glaciology.

> *the maps of the Arctic; after all, they had their own names for the snowy peaks and the frozen inlets that formed their world. It is not their loss that the map ignores them; it is our own.*
>
> Pierre Berton (1988), pp. 630–631

This work constitutes a reflection on the meaning and significance of knowledge coproduction in the field of glaciology. Starting from Seligman's (1961) classical definition of glaciology, we invoked the paradigm of *Structure–Form–Environment Interplay* (SFEI; Faria and others, 2009, 2018) to formulate a modern definition of glaciology that reveals the relevance of knowledge coproduction. The adoption of a relational view of knowledge led us to identify *five core dimensions of knowledge coproduction*: purpose, ethics, ambiguity, inclusion/exclusion, and relationships. Based on those dimensions, we delved into the decisive methodological aspects of the coproduction process, namely the definition of its purpose, the identification of participants, the organisation of the process, the recognition of ambiguity in WoKs, and the consideration of ethical implications (Brugnach and Ingram, 2012, 2017). In doing so, we were able to bring a deeper insight into the implications, drawbacks, and benefits associated with the generation of glaciological knowledge through inter- and transdisciplinary collaborative processes.

The recent literature recognises three different stages of any knowledge coproduction process: codesign, codevelopment, and codelivery (Wyborn and others, 2019; Fleming and others, 2023). Here, we propose the inclusion of an additional *preparation stage*, which entails the acknowledgment of the identity and involvement of all human and nonhuman participants, their positionality, and means to ensure their cultural and ontological safety. Such a preparation stage is fundamental to highlight and manage uneven power relations, which are often unavoidably formed from the start (Turnhout and others, 2020).

Unfortunately, many attempts at glaciological coproduction still neglect some of the aforementioned process stages, not living up to their original expectations, and limiting their scope to the mere appropriation of knowledge from the less empowered. Such failures are often related to the preservation of existing structures of power that privilege scientific knowledge over other WoKs (Carey and others, 2016; Yua and others, 2022). In glaciology, as in any other complex interdisciplinary fields, knowledge coproduction can be viewed as a process that connects different WoKs by bringing together the expertise and skills of a wide range of actors in ways that are fair and inclusive of their needs and concerns. Its essence lies in creating opportunities for the development of novel forms of knowledge, study, and action, which are capable of delving into the knowledge and wisdom of people and places. It is a process that involves working together with humans and nonhumans towards a common end, where science, even though essential, is not privileged as the sole legitimate way of knowing.

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From the perspective presented here, knowledge coproduction does not replace the scientific method, but rather complements it. By doing so, it provides a wider scope to create knowledge, which is not only scientifically robust, but also relevant and actionable for addressing real-world challenges. It is usually a gradual process, as achieving mutual understanding and trust requires considerable time and commitment from each participant. Nevertheless, it is likely to unveil deeper insights, and possibly even paradigm shifts (Kuhn, 1996), which might be difficult to attain through unilateral means.

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