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Co-production of knowledge and sustainability transformations: a strategic compass for global research networks

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An increasing number of voices highlight the need for science itself to transform and to engage in the co-production of knowledge and action, in order to enable the fundamental transformations needed to advance towards sustainable futures. But how can global sustainability-oriented research networks engage in co-production of knowledge and action? The present article introduces a strategic tool called the 'network compass' which highlights four generic, interrelated fields of action through which networks can strive to foster co-production. It is based on the networks' particular functions and how these can be engaged for co-production processes. This tool aims to foster self-reflection and learning within and between networks in the process of (re)developing strategies and activity plans and effectively contributing to sustainability transformations.

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Introduction

The recently published UN Global Sustainable Development Report 2019 identifies science as one of four levers — alongside governance, economy and finance, and individual and collective action — that together could bring about the transformations necessary to achieve the Sustainable Development Goals (SDGs). Global sustainability-oriented research networks aim to advance high-quality science relevant for understanding and sustaining the social and natural systems of Earth and identifying solutions to sustainability challenges confronting society.

Yet considering the 'wickedness' of many sustainability challenges [1,2], sustainability scholars increasingly argue that the science system itself must transform in order to fulfil its potential to foster the fundamental transformations needed to advance towards sustainable futures [3–7].[19]

Various research institutions, funding agencies and global science organizations, such as Future Earth, the Belmont Forum and the International Science Council (ISC), have echoed these calls for changes in the way that scientific knowledge is generated, shared and governed. In particular, they encourage the scientific community across diverse disciplines to build new partnerships with societal actors from government, business and civil society, and to engage in the co-production of knowledge and action. Co-production is understood as 'iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future' [11]. Under the premise that co-production processes generate new knowledge, capacities, networks, social capital and joint action, they are expected to lead to a more relevant, agile, inclusive, legitimate, impactful and innovative knowledge-action system [11,12].

Similarly, arguing for more effective knowledge-action systems for sustainable futures, the benefits of *global research networks* are increasingly highlighted. Benefits achieved or enabled by these networks include better research coordination, more international and interdisciplinary collaboration, enhanced learning through the sharing of problem understandings and solution approaches, joint value creation, more efficient use of resources, increased capacity to tackle complex problems, greater competitiveness and scholarly productivity, better linkage to policy processes and emergence of coordinated convergent action [13–19,20•,21•].

But how can global research networks engage in or advance the co-production of knowledge and action for sustainable development? In this review, we address this question and propose a strategic tool for (re)developing network strategies.

Co-production processes in global sustainability-oriented research networks

When referring to global sustainability-oriented research networks, we mean formally established entities linking researchers and other societal actors across scales to promote research and to strengthen their common effectiveness in contributing to sustainable futures [18,21•,22]. These networks are usually organized around support entities, such as a secretariat, coordination office, and/or steering committee [16].

Future Earth is a prominent example of such a global network today (www.futureearth.org). The various projects, programmes and partner organizations belonging to the Future Earth community can also be viewed as global networks themselves (see Table 1 for examples). In recent years, these networks began to address the question of how to engage in co-producing knowledge and action and began to search for innovative co-production approaches. However, several factors related to both, the evolution of the field and the characteristics of global research networks currently hinder further gains.

First, existing approaches to the co-production of knowledge and action, such as transdisciplinary research [23], action research [3] or post-normal science [24], primarily tackle sustainability challenges in local, place-specific contexts (e.g. in neighbourhoods, cities or rural areas) [25]. But many sustainability challenges, such as global change, poverty and migration, are increasingly interconnected, scale beyond particular places and can only be tackled through learning and concerted action across different contexts and on a global scale.[20] While global research networks are considered useful and effective in coordinating and governing knowledge generation across actors, places and scales [18,26–29,30•,32], much less is known about how co-production of knowledge and action can effectively be fostered across different contexts and on a global scale.

Second, the purposes, functions, and contexts of global research networks differ substantially to local, place-specific research [30•]. For example, research networks generally do not conduct research themselves, but rather aim at promoting knowledge generation by linking different types of actors across distinct scales [18,21•,22]. Hence, engagement with co-production of knowledge and action at the network level requires an entirely new toolbox of methods and approaches that reflects these differences. But guidelines, documented experiences and spaces for knowledge exchange and learning on how co-production of knowledge can be fostered at this level are generally lacking. This absence of clear roadmaps for 'upscaling' co-production can make it challenging for global research networks to engage with co-production and to integrate it into their network processes.

Third, global research networks are highly heterogeneous, featuring diverse missions, compositions, governance philosophies and activities. Some have existed for several decades; others have just recently been founded. Many of the older networks started as (inter)disciplinary science associations aiming to enhance basic science on

[19] Sustainability transformations are understood as deliberate, systemic changes in worldviews, practices, institutions and resource flows [8–10] towards more sustainable futures.

[20] By global scale, we mean structures and processes encompassing the entire world.

Table 1

Key characteristics of the 11 networks involved in the study (main mission, network structure, size, resources, funding year, role and history of co-production)

Networks	Main mission	Network structure	Size (Individual/ organizational members)	Resources (Personnel in %/operating funds per year in Euro (without personnel)	Founding year	Role and history of co-production
bioDISCOVERY	Advancing interdisciplinary collaborative research on biodiversity and ecosystem change and establishing the role of biodiversity and ecosystem function (conservation) in sustainability transformation.	Community of individual researchers and representatives of key organizations such as intergovernmental assessment bodies; governed by central hub; collaboration with societal actors mainly via interactions with intergovernmental assessment bodies.	100–1000/0	100%/<50 000	2009	Founded as an (inter)disciplinary science association (mainly natural sciences) aiming to foster co-production of knowledge with international organizations. Some members are experienced in co-production.
Earth System Governance Project (ESG)	Better understanding and improving governance of/for sustainability.	Community of individual researchers and research institutions; governed by central hub; collaboration with societal actors via research projects, interactions with UN processes and boundary organizations (established science–society interface).	100–1000/15	200%/<50 000	2009	Founded as an (inter)disciplinary science association (mainly social sciences). Co-production is seen as relevant for specific research questions. Many members are experienced in co-production.
Global Land Programme (GLP)	Fostering the study of land systems and the co-design of solutions for global sustainability.	Community of individual researchers; managed by central hub and partly autonomous regional subnetworks; collaboration with societal actors via research projects and boundary organizations (established science–society interface).	1000–5000/0	160%/50 000–500 000	2006	Founded as an (inter)disciplinary science association (natural and social sciences) involving co-production of knowledge with societal actors, mainly in regional contexts. Co-production is seen as contributing to achieve the network's mission. Many members are experienced in co-production.
Global Mountain Biodiversity Assessment (GMBA)	Fostering research on the conservation, management, and sustainable use of mountain biodiversity in a changing world and facilitating dialogue between communities of researchers, stakeholders, and policymakers.	Community of individual researchers; governed by central hub; collaboration with societal and policy actors via certain research projects.	1000–5000/0	140%/<50 000	2000	Founded as an (inter)disciplinary science association (mainly natural sciences). Co-production is seen as key to achieve the network's mission, therefore it gradually opens up to societal actors, mainly at the global scale. Some members are experienced in co-production.

Table 1 (*Continued*)

Networks	Main mission	Network structure	Size (Individual/ organizational members)	Resources (Personnel in %/operating funds per year in Euro (without personnel)	Founding year	Role and history of co-production
Global Alliance for Inter-and Transdisciplinarity (ITD-Alliance)	Strengthening and promoting the global capacity and calibre of collaborative modes of research and practice.	Alliance of individual researchers, research institutions and networks; governed by central hub with autonomy by subnetworks; collaboration with societal actors mainly via research projects.	<100/40	20%/<50 000	2019	Founded to foster co-production of knowledge with societal actors in regional contexts and with international organizations. Co-production is seen as key to achieve the network's mission. Many members are experienced in co-production.
LIRA 2030 in Africa	Building the capacity of next-generation scientists for transdisciplinary research on global sustainability in Africa.	Community of individual researchers belonging to research projects; governed by central hub; collaboration with societal actors mainly via research projects.	<100/4	300%/ >500 000	2016	Founded to foster co-production of knowledge with societal actors, mainly in regional contexts. Co-production is seen as key to achieve the network's mission. Many members are experienced in co-production.
Mountain Research Initiative (MRI)	Generate knowledge that enables decisions, actions and transformations towards sustainable development in mountains.	Community of individual researchers; governed by central hub and partly autonomous regional subnetworks; collaboration with societal actors via research projects, interactions with UN processes and boundary organizations (established science–policy interface).	>5000/10	270%/50 000–500 000	2001	Founded as (inter)disciplinary science association (mainly natural sciences). Co-production is seen as key to achieve the network's mission, therefore it gradually opened up to societal actors, mainly at the global scale. Some members are experienced in co-production.
Past Global Changes (PAGES)	Supporting research and scientific community development, in order to obtain better predictions of the future climate and environment and to inform strategies for sustainability.	Community of individual researchers; governed by central hub with partly autonomous thematic communities; collaboration with societal actors via certain research projects.	>5000/0	315%/ 50 000−500 000	1991	Founded as an (inter)disciplinary science association (mainly natural sciences). Co-production is seen as relevant for specific research questions. Some members are experienced in co-production.
Programme on Ecosystem Change and Society (PECS)	Generating the scientific and policy-relevant knowledge of social ecological dynamics needed to enable a world where human actions have transformed to achieve sustainable stewardship.	Community of individual researchers representing projects; governed by central hub; collaboration with societal actors mainly via research projects.	100–1000/20	120%/<50 000	2010	Founded as an (inter)disciplinary science association (natural and social sciences) involving co-production of knowledge with societal actors, mainly in regional contexts. Co-production is seen as key to achieve the network's mission. Most members are experienced in co-production.

Table 1 (*Continued*)

Networks	Main mission	Network structure	Size (Individual/ organizational members)	Resources (Personnel in %/operating funds per year in Euro (without personnel)	Founding year	Role and history of co-production
Southern African Programme on Ecosystem Change and Society (SAPECS)	Advancing stewardship of social-ecological systems and ecosystem services in southern Africa	Community of individual researchers representing projects; governed by network convenor; collaboration with societal actors mainly via research projects.	<100/0	10%/<50 000	2012	Founded as (inter)disciplinary science association (natural and social sciences) involving co-production of knowledge with societal actors, mainly in regional contexts. Co-production is seen as key to achieve the network's mission. Most members are experienced in co-production.
Transformations to Sustainability (T2S)	Enhancing the contribution of the social sciences to finding solutions to environmental challenges.	Community of individual researchers that belong to research projects; governed by central hub; collaboration with societal actors mainly via research projects.	<100 /15	250%/>500 000	2014	Founded to foster co-production of solution-oriented knowledge with societal actors, mainly in cross-regional contexts. Co-production is seen as key to achieve the network's mission. Most members are experienced in co-production.

sustainability topics. Over the years, some of them gradually opened up to co-production processes with other disciplines or societal actors because they found it important for achieving their mission, while others kept their focus on basic science. Some of the newer networks, in turn, were explicitly founded for the purpose of fostering co-production of knowledge and action for sustainability transformations. Considering their diverse purposes and history, all these networks have different strengths and face different challenges with regards to co-production.

Scholarship on research networks has only recently turned to issues of knowledge co-production for sustainability [21•,31•]. For example, Keeler *et al.* [21•] identified different models of collaboration that can support accelerated learning regarding co-production processes within a network: (1) solution adoption; (2) solution consultation; (3) joint research on different problems; and (4) joint research on similar problems.

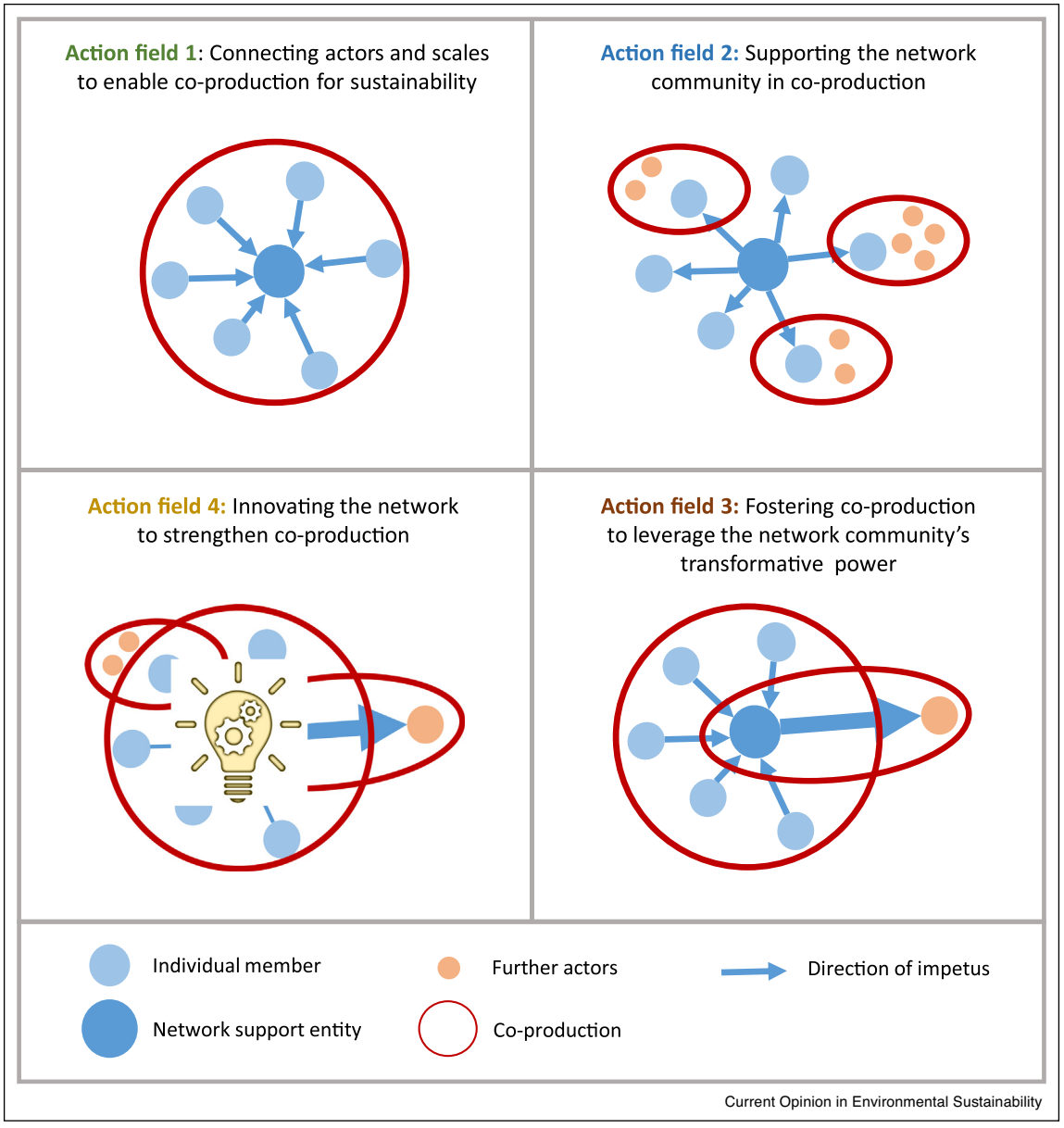
At the same time, research on knowledge-action networks [20•,33•] and research-policy networks [34•] form a relevant body of literature on which to draw. These allied networks are constructed around societal actors from government, business, and civil society that aim at joint leadership for systemic change towards sustainable futures. Hence, while they focus less on academic knowledge production than the research networks investigated in our study [15,20•,33•], much can be learned from them about the capacities of networks to foster co-production processes.

Studies applying a functional perspective that highlights what a network must or can do to achieve its own aspirations are particularly insightful for this purpose. Identified functions include visioning, organizing, resourcing, learning/research capacity development, assessing, advocating and prototyping [20•], as well as knowledge management, amplification and advocacy, community building, convening and mobilizing resources [16]. In addition to these generic functions, networks can adopt different roles or strategies to foster sustainability transformations. Examples include the roles of knowledge brokers versus entrepreneurs [33•] or the support of members versus joining forces for joint agency [16]. These strategies differ in their basic assumptions regarding what type of change agency is striven for and where it is considered to unfold. Whichever strategy is chosen, these agencies usually do not emerge automatically, but network support entities can facilitate their creation [16]. Careful boundary management (with multidimensional accountability towards different actors involved), communication, translation and mediation are key [18,35,36].

Learning to enhance the capacity of global research networks for co-production

To address the above-mentioned lack of knowledge and experience with co-production at the network level,

Figure 1



Conceptual definition of the four fields of action and the respective location of co-production.

representatives of eleven global sustainability-oriented research networks volunteered to engage in a joint reflection and learning process reinforced by systematic research. The overall goal of this joint research process was to investigate how global research networks can effectively contribute to co-production of knowledge and action towards sustainability transformations. The focus was on exploring the networks' particular functions and how these can be brought to fruition for co-production processes. In particular, we asked the following questions:

- What action fields regarding co-production of knowledge are relevant for global sustainability-oriented research networks?
- What specific activities do these networks implement in these action fields?
- What are potentials and challenges?

Through this effort, we generated a strategic tool designed to foster self-reflection and learning regarding the development of promising network strategies and

action plans to more effectively contribute to sustainability transformations. The tool enables the characterization of a network, to create joint understanding among network members about the potentials and limitations of the existing strategies and, finally, to identify priorities for further strategic development by considering the particular functions networks have for co-production [37].

While all networks involved in this study aim to foster knowledge production for sustainable futures, their missions, composition, governance philosophies, activities and commitment to co-production are very diverse. An overview of the eleven networks involved in this study can be found in Table 1 and Figure 3. Details on the applied method are presented in Appendix A.

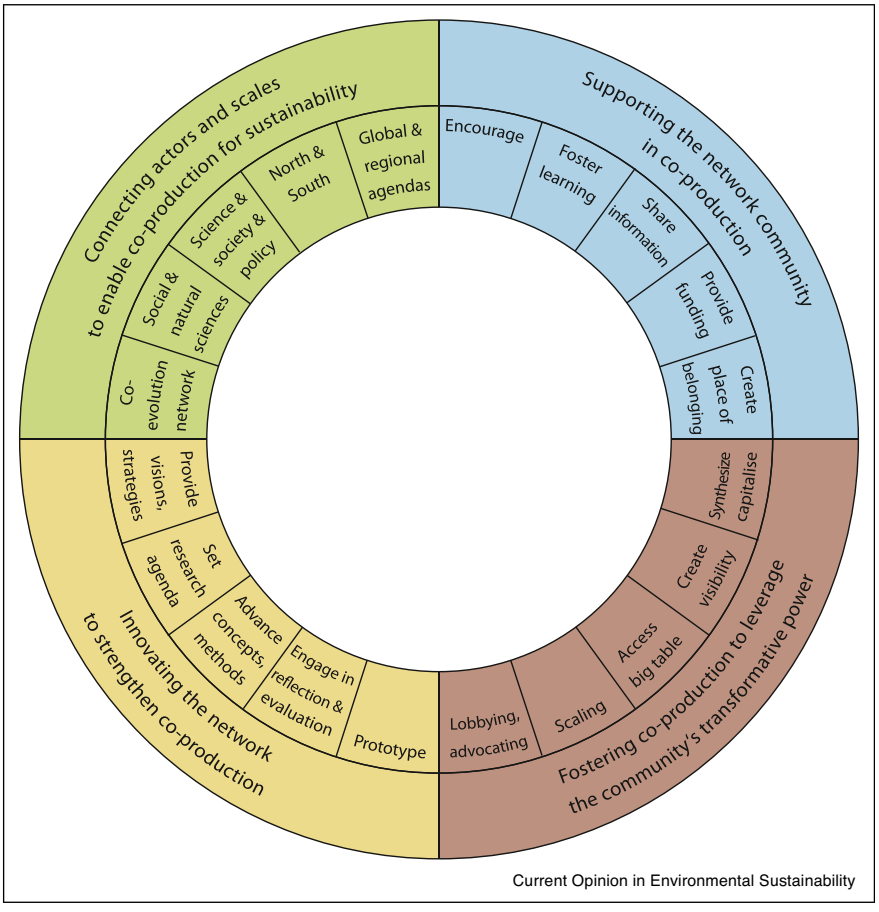
Action fields for fostering co-production in global research networks

Comparison of the eleven networks, while taking into account the insights of the literature review, allowed us to identify four generic and interrelated fields of action through which networks seek to foster co-production (for a conceptual definition, see Figure 1, and the text below). Each field of action highlights a particular network function with specific change agency and location of co-production [16,33•]:

1 Connecting actors and scales to enable co-production
2 Supporting the network community in co-production
3 Fostering co-production to leverage the network community's transformative power
4 Innovating the network to strengthen co-production

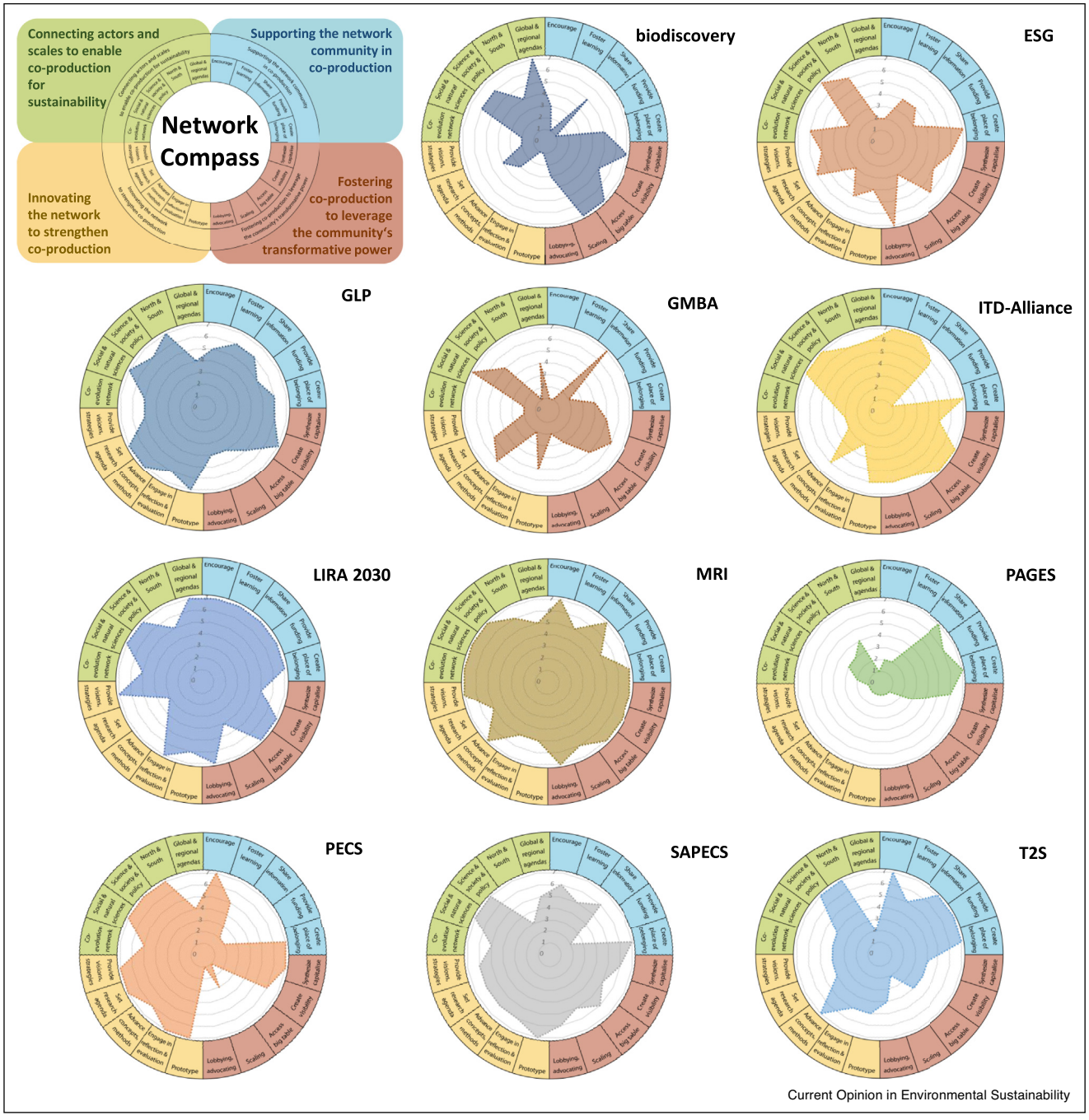
Each field of action is divided into five subfields embracing the different activities of the heterogeneous networks. Specific activities (e.g. organisation of a conference), however, can contribute to several fields (e.g. connecting actors from the global North and South (action field 1) and create a place of belonging for the community (action field 2)). Some networks emphasize equally all four action fields, others have a specific focus (see Figures 2 and 3).

Figure 2



'The Network Compass': four generic fields of action, each with five subfields, through which networks seek to foster co-production of knowledge for sustainability transformations.

Figure 3



The studied global research networks' strategic emphases on the fields of action of the Network Compass (1 = no emphasis [center of circle]; 7 = high emphasis [outer perimeter of circle]).

Connecting actors and scales to enable co-production

Characteristics

The first field of action highlights the function of convening actors across disciplines, sectors of society, places and scales [16] and building a community that engages in co-production of knowledge and action. The network itself is the site of the co-production processes and agency emerges among the different members in the network. The network support entity acts as a broker [33•], connecting and organizing interested actors around

sustainability-related topics and creating conditions favourable for co-production processes to emerge. This field of action is a precondition for the other three action fields.

Activities

All networks in this study undertook these kinds of activities, but they differed in their perception of who should be involved in co-production and what the outcome should be. Some prioritized intra-academic knowledge co-production between researchers from different disciplines (e.g. social and natural scientists) or distinct geographic regions (e.g. global North and South); others prioritized the involvement of societal actors (e.g. decision-makers, practitioners, civil society) and the generation of joint action. Establishment of connections between different scales (e.g. global and regional agendas) was also frequently mentioned. Finally, several viewed the very evolution of the network itself to be a result of the co-production process.

Network support entities convene diverse actors across scales through various means, such as international or regional face-to-face meetings (e.g. conferences, working groups), online gatherings (e.g. webinars, interactive platforms), the establishment of science–policy interfaces (e.g. via boundary organizations), member/expert databases and by enabling inclusive participation (e.g. through selection of committee members and targeted funding to less well-resourced participants). These activities require careful planning and facilitation, as well as accountability towards the interests of different parties (e.g. conference formats that are made accessible to non-scientists or non-native English speakers) [18, see also Refs. 30•,38] (see also Appendix B).

Potential and challenges

All networks in this study established vibrant communities of practice engaging in co-production processes with various outcomes, including facilitation of new knowledge and ideas, social relations, learning tools and curricula, standardized monitoring and evaluation approaches as well as institutionalized forms of collaboration with boundary organizations, such as international NGOs, UN organizations and intergovernmental assessment bodies, as for example the Intergovernmental Panel on Climate Change (IPCC), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Convention on Biological Diversity (CBD). But the establishment and maintenance of inclusive partnerships between previously disconnected actors was a major challenge for all networks. Depending on the network history, this concerned inclusion of further disciplines, societal actors or geographic regions. For example, despite strongly prioritizing the inclusion of researchers from the Global South, — for instance by organizing conferences in different parts of the world and by attending to issues of diversity when choosing keynote speakers or members of committees, — researchers from the Global North remain overrepresented, likely because the academic field is more firmly established at their universities and because of the greater availability of funding [26,39].

These findings are in line with existing literature, suggesting that formal networks can mainly identify, enhance, add value to, expand or otherwise transform existing or potential relationships, but they cannot easily impose such relationships [16,18].

Supporting the network community in co-production

Characteristics

The second field of action focuses on the function of strengthening the agency of its members for co-production. In this case, the individual network members implement co-production processes in their contexts (also called place-based co-production). The network support entity provides services to the members [16,20•].

Activities

All networks studied provided such support services, though to differing degrees. Some encouraged their members to practice co-production (e.g. by highlighting its value in their science plans) and to share guidelines and best practices on how to operationalize it. Others organized learning opportunities, such as webinars, massive open online courses, practical training courses, coaching workshops or working groups to foster co-production competences. The provision of funding for working groups or transdisciplinary research projects was another important service. Finally, the creation of a 'home' and place of belonging for researchers engaged in co-production was another frequently mentioned way of supporting network members (see also Appendix B).

Potential and challenges

Networks that are heavily engaged in supporting co-production processes among their members generally appear very satisfied with the results. In particular, opportunities offered for competence development, peer-to-peer learning and implementation of transdisciplinary research are usually very well attended and received. As co-production approaches still represent a niche in many universities, network members also highly appreciated the empowerment they experienced when feeling part of a community of like-minded people. However, providing such services requires considerable financial means and is therefore mostly specific to networks which succeed in attracting larger donors for this purpose. Moreover, it requires a network community that is keen to learn and implement co-production approaches. Hence, networks with a more academic tradition and a focus on more disciplinary or global questions often find it

harder to motivate members and identify appropriate support measures.

Fostering co-production to leverage the network community's transformative power

Characteristics

The third field of action relates to the function of coordinating the efforts of its members and of acting as a collective agent [16,20•,33•]. Networks aim to be more than the sum of their parts: by combining the expertise and connections of all their members, they can speak with one voice and wield more influence than any individual [15]. Co-production can be a key ingredient in this process. First, co-production activities are needed within the network community to enable the network to become a collective agent and to permit the network support entity — or other representatives — to speak on behalf of the community. Second, as a collective agent, the support entity can engage in or coordinate co-production with additional societal actors.

Activities

Required co-production within the network community is achieved through activities related to synthesis of and capitalization on multiple research findings and experiences. The network support entities support this by mobilizing members, developing conceptual frameworks and synthesis methods, coordinating cross-scale collaboration and involving societal actors to ensure societal relevance. Engagement and coordination of co-production with additional actors is performed based on this consolidated knowledge and the global community of expertise. Specific activities organized by network support entities include generating visibility via communication of findings through co-produced websites, magazines and policy briefs; participation in policy events; use of common weight to access 'big tables' (e.g. events with powerful economic actors); advocacy; and lobbying for their interests (e.g. with science funders, UN organizations or national governments). In this respect, several networks mentioned activities having the goal of fostering shifts in academic culture as a whole (e.g. reward systems, funding structures, career paths and institutions favourable for co-production). Mediating between scales is another key dimension (e.g. helping to upscale and out-scale contextualized research insights and downscale global findings) (see also Appendix B).

Potential and challenges

Many of the networks in this study successfully coordinated interdisciplinary co-production processes, often in collaboration with societal actors. The most widespread example here is collaboration with intergovernmental assessment bodies and boundary organizations, such as the IPCC, IPBES and CBD. Several networks co-designed respective analytical frameworks with these bodies, communicated them to their communities to channel assessment-relevant research efforts, coordinated synthesis processes within targeted working groups (thematically and geographically) and, finally, fed the generated synthesis products back into these global assessment processes. However, all networks found it challenging to engage in co-production processes with powerful actors capable of effectively initiating wider societal transformation processes towards sustainability. Challenges involve identification of societal partners; finding joint, knowledge-related interests; harmonization of working processes; and generation of sufficient financial and personnel capacities to implement the activities.

Innovating the network to strengthen co-production

Characteristics

The fourth field of action relates to the need to foster innovation within the network to strengthen its capacity to perform co-production in all three other fields of action. The network support entity acts as an entrepreneur aiming to transform the network itself [20•,33•].

Activities

Means to foster conceptual, theoretical, methodological and practical innovation include the development of novel visions and strategies that detail a network's theory of change, pathways to impact and the role of co-production for the research field. Co-designing research agendas together with societal actors at different scales can focus research efforts on key questions relevant for sustainability. Investment in conceptual and methodological advancement to integrate co-production is also often stressed (e.g. writing state-of-the-art papers on the community's co-production approaches or sustainability-relevant insights). A few networks are setting up novel approaches to experiment with and create models of co-production at the network level together with key societal partners (prototyping). For example, some networks tested new science–society interfaces via boundary organizations, such as INGOs, to find a better way to bridge knowledge and action at different scales [see also Refs. 26,28]. Finally, regular self-reflection and evaluation exercises to enhance adaptive monitoring and learning for improvement are considered key (e.g. regular retreats with the steering committee, learning exchanges among coordinators of different networks, learning studies) (see also Appendix B).

Potential and challenges

Networks with different co-production histories have different potentialities and face different challenges when attempting to innovate. Networks founded for the purpose of fostering co-production for sustainability typically benefit from the fact that they already include researchers from many different disciplines as well as societal actors and that these share fundamental epistemological assumptions regarding the significance of co-production. Hence, their co-production approaches are

innovative and thought–through from the start; the entire network can be regarded as a prototype. These networks are challenged to execute this pioneering role without having role models that could provide guidance for suitable structures and processes while simultaneously being under pressure to reshape wider science systems in order to improve the conditions for this type of research.

Networks which started as (inter)disciplinary science associations have fostered innovations by adapting their science plans, research agendas and governance. However, as their individual members have diverse perspectives on the value of co-production — ranging from enthusiastic to sceptical, — these networks face challenges in promoting co-production innovations while simultaneously navigating a mix of epistemological assumptions. In addition, determining what the added value of co-production can be for their research and finding joint interests with societal actors can be challenging.

Regardless of how promising innovations are defined, all the research networks expressed difficulties in deliberately fostering fundamental innovations (see also Refs. [29] and [18]). This may be because innovations favouring co-production often require fundamental transformations of values, social relations, competencies, routines and existing research infrastructures. Hesitant action lacks transformative power, but pushing too hard can quickly become counterproductive when it provokes resistance from members and other actors representing different epistemological values and interests. This poses a risk to the network, as the introduction of new functions can hamper a network's capacity to fulfil its original functions [34•] and to meet the expectations of its members. In addition, global research networks are usually rather loose structures with limited funds and, absent strong hierarchies, unable to fully control network activities [17].

Concluding remarks

In this review, we explored how global research networks engage with co-production of knowledge and action for sustainability by studying their specific functions. By doing so, we identified four fields of action, each characterized by five subfields.

The four fields of action reveal that incorporation of co-production at the level of global research networks requires a different perspective on co-production processes than is usually applied in individual research projects. In a research network, co-production can be facilitated by individual network members in specific research contexts, by the community of network members together, and/or by the network support entity itself. Fundamental innovation in the science system may be necessary to enable co-production to fulfil its potential. Hence, to foster effective co-production in such settings, global research networks need to think about: how the network support entities can support the members in co-production (action field 2); how they can convene these members and enable co-production among them (action field 1); how they can engage in co-production themselves to leverage their community's transformative power (action field 3); and how they can foster innovation to improve the conditions for co-production (action field 4).

Although networks can fruitfully set priorities only in some fields of action (e.g. supporting their members or leveraging members' activities), tensions can emerge in some situations when network members do not agree on priorities. For example, conflicts can emerge when the network support entity pushes for innovations in co-production (action field 4) while neglecting co-evolution of the network (action field 1), or supporting community needs (action field 2).

The four action fields proved to be helpful for structuring the studied networks' very diverse approaches to co-production of knowledge and action, but also as a heuristic for fostering self-reflection, knowledge exchange and learning within and between the networks. Learning within and between global research networks is crucial, as incorporation of co-production processes is a challenging task that requires novel, untested strategies and fundamental transformations of the very networks themselves and/or the relevant science systems. Application of the heuristic for learning does not resolve whether given activities are better or worse than others or how specific activities should be implemented. This depends on each network's envisioned goals, co-production history, member composition, epistemological assumptions and additional context-specific conditions. However, it does aid systematic reflection on the specific potentials and challenges related to the functions of a network.

Hence, the design and implementation of co-production processes for sustainability can only be achieved through carefully designed, step-by-step approaches, while acknowledging the mentioned variations and functions. To identify promising processes, global research networks must develop network-specific theories of change that specify how activities related to the four fields of action might best be combined to achieve the envisioned goals. This involves reflections on the significance of co-production in relation to the self-conception of the network, its specific scientific topics and societal transformation goals, the basic network structures and processes in place as well as possible conflicts and synergies within and between different action fields. Guidelines to apply the framework as a strategic tool are presented in Schneider and Tribaldos [37].

The Network Compass represents an important starting point for structuring a process to systematically reflect on

how global research networks can contribute to co-production and sustainability transformations. But several open questions remain regarding which approaches and theories of change are most promising [40]. Hence, more reflexive research is needed that places key social learning processes at the core to elucidate precisely what kind of co-production activities and organizational formats of networks contribute most effectively to sustainability transformations and ensure these are operationalized.

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Appendix A. Methodological approach
Case selection
Our study is based on an investigation of eleven global research networks belonging to the Future Earth initiative. Future Earth is a network of networks and individuals who are collaborating for a more sustainable planet. It was created in 2015 as a global initiative to strengthen the interface between policy and science and builds on more than three decades of global environmental change research. Six of the investigated global research networks are officially endorsed Global Research Projects of Future Earth (GLP, GMBA, PAGES, biodiscovery, PECS, ESG); one is a regional network of one of them (SAPECS); one is a partner of Future Earth (MRI); two are special initiatives of the Future Earth founding members ICSU and ISSC that are aimed at strengthening the Future Earth initiative (LIRA 2030, T2S); and one is an independent network collaborating with Future Earth (ITD Alliance). While all of these networks have different structures, epistemological assumptions, aims and histories, they all share the general goal of fostering science relevant for sustainable development. Moreover, they are all research centred and span actors from around the globe.

To select the networks, we used a purposive sampling strategy, combined with convenience elements. It focused on the following two main criteria: (a) maximum variation of network types in terms of network structure, duration and aims and differing co-production approaches and histories (see Table 1 and Figure 3); (b) willingness of network representatives to contribute to the study and engage in reflection on their approaches to co-production of knowledge.

The study began with four networks that have their headquarters in Switzerland. Based on preliminary analyses of these networks, we gradually involved further networks with alternative structures and approaches. For example, as the four initial networks were strongly natural-science based and mostly included members with relatively little co-production experience, we looked for networks dominated by social scientists and/or with extensive co-production experience. We continued adding new networks until we reached conceptual saturation. This means that introduction of new networks into the analysis generated new insights into possible network activities, but it did not generate insights requiring us to revise our emerging conceptual framework.

Co-production method
Our study was itself based on a co-production process. Co-production is an appropriate approach for developing a framework that aims to support networks in enhancing their effectiveness to contribute to co-production and sustainability transformations, as it combines rigorous scientific thinking and analysis with the experiences of the targeted actors [41,42]. The actors involved can be grouped as follows: 'core team' (the first and second author of this article); official representatives of the eleven selected global research networks (e.g. coordinators, managing directors and so on, all co-authors of this article); and members of some of these networks (GLP, ESG, Lira 2030). They all contributed to the co-production process through an iterative, four-step approach.

First, the networks' co-production-related strategies, approaches and activities were assessed. To achieve this, the core team conducted interviews with the coordinators of the networks and analysed their websites, strategy documents and other available resources, such as scientific papers. In addition, to gather the perspectives of network members themselves, the core-team and representatives of some networks organized workshops at network gatherings where various members discussed potentials and limitations of co-production at network

level. Data were analysed with procedures of qualitative content analysis [43]. Insights of these analyses were summarized and shared with the actors involved.

Second, to deepen the analysis and enable learning and co-production between the different networks, several workshops were organized (four workshops in Switzerland with GLP, BioDiscovery, GMBA, PAGES and MRI; one workshop in South Africa with GLP, SAPECS, Lira 2030, ITD Alliance, T2S). In these workshops, we used different dialogue methods that help structure group conversation processes aimed at enhancing self-reflection and jointly creating meaning and shared understandings [44]. Further, the empirical research insights generated in step one were used to nurture the discussions.

Third, based on the insights of the two previous steps, the core team developed a draft of the framework. They first summarized the collected data in table form and then analysed the networks' co-production approaches in an iterative process of concept identification and comparison to identify recurrent patterns of similarities and differences. This analytic process was enriched by insights gained through the literature review, namely on network functions. The identified four fields of action highlight four different network functions with specific change agency and location of co-production. The five subfields cover main activities implemented by the analysed networks. While they cover most aspects mentioned in the literature, inclusion of additional networks to the analysis might reveal further subfields. Fourth, the tool was validated and refined in a workshop with the Swiss-based networks, and in a subsequent web-based exchange with all involved networks. This step involved reattribution of the networks' co-production activities to the four action fields and their subfields.

Appendix B. Activities conducted by the 11 global research networks to tackle the four fields of action

Fields of action	Subfields	Activities
Connecting actors and scales to enable co-production for sustainability	Global and regional agendas	Organize events in the regions to discuss global agendas, such as the 2030 Agenda, Paris Agreement, and Sendai framework; foster research in specific regions related to these global agendas; bring the regional agendas and insights into global policy processes and international conferences.
	North and south	Organize conferences in countries of the global South; provide funding for participants of the global South; invite people from the global South as keynote speakers as well as working group and steering group members; strengthen capacities of researchers of the global South; collaborate with South-based organizations/networks; employ open-access strategies enabling South-based researchers to access information and research.
	Science, society and policy	Invite decision-makers, artists and other societal actors to conferences, make conferences attractive for them (e.g. let them suggest topics and formats, giving them roles and spaces, interactive sessions, local stakeholder events, TD processes around ugent societal issues); organize short-term and long-term (regional) science–policy interfaces, e.g. by collaborating with boundary organizations such as Stakeholder Forum; participate in conferences and policy processes organized by societal actors; enable interactions with UN or intergovernmental processes (e.g. IPPC, IPBES); connect with science policy actors (e.g. funders).
	Social and natural sciences	Encourage/select interdisciplinary conference themes and working groups; establish member/expert databases.
	Co-evolution network	Develop strategies/science plans in a participatory and inclusive way; involve a variety of actors across scales in the steering committee; conduct surveys to identify member needs; demonstrate commitment to integrate members' needs/feedbacks in network management.
Supporting the network community in co-production	Encourage	Highlight the significance of co-production in network visions, science plans and/or on website; encourage working groups to develop co-production plans for their work; showcase co-production examples.
	Foster learning	Organize webinars, online courses (MOOCs), trainings, coaching/mentoring, self-reflection workshops and/or conference sessions/working groups on co-production (basic competences and experience exchanges); develop guidelines on how and when to do co-production; enable learning by doing.
	Share information	Publish newsletters/website info to share funding opportunities, calls, special issues, policy reports, and so on.
	Provide funding	Fund co-production research projects (seed money and full projects), learning opportunities and/or participation in science–policy interactions or conferences.
	Create place of belonging	Enable community building of like-minded people interested in working in co-productive ways.

(*Continued*)

Fields of action	Subfields	Activities
Fostering co-production to leverage the community's transformative power	Synthesize and capitalize	Coordinate synthesis relevant for co-production and sustainability transformations (regarding topics and processes); publish special issues; include societal actors in synthesis processes (for defining topics or conducting the synthesis); standardize methods/concepts and align synthesis to needs of global assessment bodies such as IPBES, IPPC; encourage capitalization of co-production experiences of the community and develop community standards; encourage joint paper writing on lessons learned.
	Create visibility	Contribute to public debate and decision-making through targeted publications such as websites, journals/magazines, policy briefs, videos, high-level reports, presentations and open-access databases featuring co-produced, consolidated data, knowledge, and experiences; co-design the communication channels with the target groups.
	Access big tables	Engage with global assessment bodies such as IPBES and IPPC; connect to UN processes such as the 2030 Agenda, CBD and regional tables, such as the European Commission (e.g. by nominating members, participation in task forces and steering committees); interact with international NGOs, UN organizations (e.g. UNCCD) or funders; participate at key policy events, round tables and so on.
	Scaling	Help scale up findings from different regional contexts (e.g. as part of global assessment processes) and localize global findings to the regions (e.g. when co-designing research agendas for certain regions); contribute to link actors and topics across scale; nominate researchers from certain regions to global processes (e.g. researchers from Africa for the UN high-level political forum for sustainable development); scale out capacity building on co-production methods.
	Lobbying/advocating	Engage with governments, businesses, and civil society and speak up for the networks sustainability-oriented key messages (e.g. via high-level ambassadors/fellows/champions, open letters); engage with science policy actors (e.g. global forum of funders, academies, universities) to lobby for sustainability science, foster a culture shift towards co-production and co-develop novel funding schemes (e.g. via establishment of NORFACE–Belmont Forum call for proposals for Transformations to Sustainability or national science funders); lobby for particular concerns, such as the value of social scientists.
Innovating the network to strengthen co-production	Provide visions, strategies,	Develop and communicate the networks' theories of change (what they aim to contribute to sustainability transformations, what the role of co-production can be and their specific roadmap to co-production); conceptualize the link between the research topics, co-production and sustainability transformations in the science plan.
	Set research agenda	Propose research agendas that link scientific advancement to societal relevance; highlight knowledge gaps related to co-production; co-design the research agendas with societal actors from different scales (e.g. through contextualized visioning workshops or surveys to gather societal actors knowledge needs).
	Advance concepts, methods	Foster conceptual and methodological advancement to enable co-production of knowledge useful for sustainability transformations (e.g. needed frameworks acknowledging multiple perspectives, new synthesis methods for connecting contextualized understandings and global drivers as well as promising co-production approaches and theories of change).
	Engage in reflection and evaluation	Organize regular reflections and retreats within and between networks to scrutinize the network activities against the background of its theory of change; encourage self-reflection among network members (e.g. as part of the formal reporting processes); conduct a 'learning study'/accompanying research to integrate external perspectives.
	Prototype	Experiment with (novel) approaches to co-production in the network themes and create model cases of co-production others can follow (e.g. through TD projects and novel partnerships with societal actors/boundary organizations to co-design research agendas, enhance dialogue and/or co-implement transformative actions; incubators for new ideas; novel approaches to syntheses that reflect various actors' values); design novel training curricula approaches.

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