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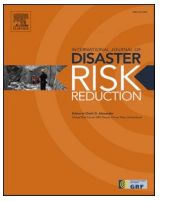
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Capacity development for locally-led knowledge co-production processes in Real World Labs for managing climate and disaster risk

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ABSTRACT

Knowledge co-production processes are increasingly used to promote transdisciplinary collaboration and integration of knowledge across scales to better understand and govern complex sustainability challenges. However, existing literature tends to overlook the capacities and skills required for designing, researching and facilitating such processes, and the empirical evidence base demonstrating their benefits remains narrow. For example, practical guidance and training for locally-led design and implementation of knowledge co-production processes is scarce. In this paper, we explore capacities for enabling such processes, and the skills that underpin them as well as those that emerge from them based on lessons learned from the implementation of the DIRECTED project. The project develops the capacity of practitioners from four regional Real World Labs in Denmark, Italy, Germany, and Austria/Hungary to design, research and facilitate knowledge co-production to address their local and regional disaster risk and climate adaptation-related challenges. The process seeks to support knowledge integration and influence integrated

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planning, policy and interoperable tool development through transdisciplinary collaboration. The paper puts forward a structure for the four key capacities (collaborative, systems thinking, creative and reflexive capacities) and related skills needed by both Real World Lab practitioner hosts and academic researchers, to enable knowledge co-production, along with findings demonstrating how these have influenced the evolving activities designed by Real World Lab hosts. Reflections are provided on how to inform knowledge co-production applications to better integrate considerations of capacities and skills required by practitioners and academics.

1. Introduction

The landscape of disaster and climate risks is evolving, as climate change and global socio-economic developments are rapidly producing more complex constellations of risks. On one hand, climate change is exacerbating the effects of hydrometeorological hazards [1], and on the other, changes in exposure and socio-economic vulnerabilities are increasing their impact. This trend is likely to continue considering the rate of global annual mean temperature rise, e.g. leading to an intensification of many climate and weather extremes and the increased exposure of people and assets [2]. The number of those affected is growing (reaching 4.03 billion between 2000 and 2019), and the economic losses have more than doubled from $1.63 trillion to $2.97 trillion during the same period [3]. The European Environment Agency predicts that economic losses from coastal flooding in Europe alone could exceed 1 trillion euro per year as a result of interacting climate-related hazards and non-climatic risk-drivers such as the environmental, social and economic conditions [4].

Associated with these changes, the increasing complexity of interconnected socio-ecological (and technical) systems continues to generate new dependencies and vulnerabilities that cross national or geographic boundaries [5–7]. Climate change and disasters present wicked problems, characterised by ill-defined parameters and interdependencies, across multiple levels and scales, and subject to uncertainty [8,9]. To account for such evolving trends, risk modelling and risk governance require a shift from traditional single hazard or risk-based approaches to multi-hazard and systemic perspectives that encapsulate the dynamics of hazards, exposures, vulnerabilities, socio-economic and climate conditions to design effective adaptation strategies [10,11]. Despite advances in science and technology to predict and model risk, barriers such as the gaps between users and producers of risk information, limited understanding of decision-making needs, or overly technical or inaccessible data, are curbing the use of knowledge for risk-informed decision-making in policy and practice [7,12–15]. Furthermore, a lack of interoperability across climate and disaster risk communication, governance and data/modelling systems amplifies the challenge [16].

Addressing the evolving complexity, uncertainty, with multiple hazards and risk drivers, paints a challenging, and even 'messy' picture with fragmented policy processes and frameworks for Disaster Risk Reduction (DRR) and Climate Change Adaptation (CCA). This necessitates a more harmonised approach by practitioners, scientists and policymakers implementing Disaster Risk Management (DRM) alongside climate adaptation at the local and regional level. Complex institutional arrangements with limited coordination, disciplinary silos, as well as uncertain funding and political landscapes often hinder the integration of CCA and DRR [17]. Although the availability of both technology- and process-based 'innovations' for DRM and CCA is increasing, collaboration and knowledge co-production between researchers and practitioners across disciplines is urgently needed to influence policy and practice [18]. Blending DRM and CCA requires a transdisciplinary approach that integrates disciplines, approaches and knowledge systems that can stimulate greater impacts and efficiency of resources on-the-ground [19,20].

Knowledge co-production provides practical ways forward to address transdisciplinary challenges by recognising multiple ways of knowing and doing and involving more diverse stakeholders in bridging the usability gap between users and producers of risk information [12,21]. Here we define knowledge co-production as the "iterative and collaborative processes involving diverse types of expertise, knowledge and actors to produce context-specific knowledge and pathways towards a sustainable future" ([22], p. 183). However, the practical guidance and skills required to support the implementation of knowledge co-production processes is scarce, and empirical evidence demonstrating its added value or impact remains limited [23]. Some guidance on the praxis of co-production exists, for example see Tandem Framework [12,21], but there is a gap in understanding the capacities required, by whom, to embed co-production into local-led governance processes.

Building local ownership and strengthening local capacity, training and skills has always formed a key component of development activities, for example in community-level CCA [24]. However, capacity building for DRR has partly failed to bring about change because of a lack of understanding and addressing systemic problems including clashing principles, power imbalances, institutional barriers, and a lack of motivation for change [25]. These systemic issues can be addressed by developing capacities of intermediaries from practice and academia for transdisciplinary collaboration and knowledge integration to help bridge the science-policy-practice interface. Persons trained and dedicated for such tasks have been described as learning champions [26], boundary spanners [27,28], knowledge brokers [27,29,30], policy entrepreneurs [31], (applied) transdisciplinarians [32,33] or integrators [34]. Transdisciplinary projects, such as those funded by the European Commission, can stimulate such intermediary roles for practitioners based in local or regional authorities e.g. city hub liaisons for climate services co-design in collaboration with liaising academics in local universities [35]. Collaborative and partnership arrangements such as knowledge networks and Communities of Practice [36] or experimental arrangements like real-world labs [37] offer a new opportunity to build capacity for emerging transdisciplinarians in practice and academia, to lead and support, knowledge co-production processes in local governance contexts. Such experimentation can support knowledge exchange and learning across levels and scales can help support actors to develop integrated solutions to climate-related

challenges and sustainability transitions [38]. Developing institutional capacity for integrating DRR and CCA knowledge, relationships, processes is crucial [39] and strengthening local/regional capacity for knowledge co-production is a means to this. That is, strengthening community level capacity through transdisciplinary co-creation activities draws on local knowledge while building ownership and legitimacy for adaptation interventions and policy, see for example [40].

In this paper we present a novel approach to capacity development for knowledge co-production targeting Real World Lab (RWL) practitioner hosts in four regions exposed to extreme and multiple climate and disaster risks across Europe, within the DIRECTED project.[1] We will present how key capacities and skills targeting knowledge co-production have been identified and developed, along with first findings demonstrating how these have influenced activities and outcomes in RWLs, as well as the emerging capacities of academic researchers supporting RWLs. Based on these experiences, reflections are provided to help guide such capacity development for knowledge co-production with practitioners and academic researchers.

2. Methodological approach

2.1. DIRECTED project context and Real World Lab setting

The results shared in this paper draw on the DIRECTED project (Horizon Europe, 2022–2026) aiming to increase resilience to extreme weather events and foster disaster-resilient European societies by promoting interoperability of data, models, information, communication and governance to support DRM and CCA. The project established four RWLs across Europe, hosted by practice-based consortium partners i.e. practitioners with institutionalized responsibilities to handle day-to-day challenges surrounding DRM and/or CCA in their regions through government agencies, private sector and NGOs. The DIRECTED consortium consists of 18 partners, with 12 considered academic research partners (including scientists from various scientific disciplines and small-medium enterprises, bridging modelling, communication and governance expertise) who provide expertise exchange with RWL host practitioners (6 partners). In certain RWLs, practitioner hosts have technical support from regionally based partners based in research or practice. Academic researchers (i.e. trainers) with expertise in social sciences and stakeholder engagement, designed and coordinated a capacity development programme [41] to support the RWL hosts on their context-specific transdisciplinary knowledge co-production journey. Additional technical, governance and communication expertise within the consortium's academic research partners was accessible depending on the specific interests and evolution of the RWL.

These RWL hosts are as follows, while Fig. 1 presents an overview of the different RWL contexts and partner roles.

- Capital Region of Denmark hosted by Region Hovedstaden with technical support from the Technical University of Denmark (DTU).
- Emilia-Romagna Region hosted by Civil Protection of the Emilia-Romagna Region (ARSTPC-ER) together with the Regional Agency for Prevention, Environment and Energy (ARPAE) Hydrometeo Service Civil Protection Functional Centre, with technical support from GECOSistema.
- The Danube region is led by Genillard & Co. a consulting company and reinsurance broker (based in Munich) with technical support from Potsdam Institute for Climate Impact Research (PIK). This RWL has a sub-region in Zala County Hungary, led by Zala Special Rescue Team, a first responder organisation of civilian volunteers.
- The Rhine-Erft region in the federal state of North Rhine-Westphalia, Germany, led by the Erftverband (waterboard).

RWLs are increasingly used to facilitate collaborative transdisciplinary learning environments that support innovations among a mix of relevant stakeholders, including collaboration between researchers and practitioners [42], to address complex sustainability [37,43], or climate change [44] related challenges. In DIRECTED, the RWLs are built around stakeholder needs, using tools and knowledge to facilitate discussions, exchange expertise, and iteratively develop solutions that are both practical and applicable to real-world challenges. The knowledge co-production activities in each RWL are designed to enable the delivery of the project's goals, which include, 1) applying governance frameworks (Risk-Tandem Framework[2]) that support integrated and interoperable DRM and CCA governance, information, communication and data/modelling solutions, 2) co-developing and applying technical tools to meet specific needs (Data-Fabric[3]), and 3) building capacity among RWLs to sustain engagement and tools beyond the lifespan of the project [16,45]. Each of the RWLs aim to create a collaborative learning and innovation environment involving a mix of local, regional, and/or national stakeholders relevant for managing climate and disaster risks. Each RWL has different priorities and interests for steering the knowledge co-production process, based on the opportunities presented by the DIRECTED project e.g. access to specific expertise, data,

[1] DIsaster Resilience for Extreme ClimaTe Events providing interoperable Data, models, communication andgovernance (DIRECTED) project is an Innovation Action under the Civil Security for Society, Disaster-Resilient Societies programme of Horizon Europe (2022–2026) funded by the European Union. Grant No: 101073978.

[2] The Risk-Tandem Framework combines risk management approaches and tools with iterative co-production processes as a cornerstone of its implementation, in efforts to promote the co-design of fit-for-purpose solutions, methods and approaches contributing toward strengthened risk governance alongside stakeholders, see more in Parviainen et al. [45].

[3] The Data Fabric is proposed as a novel open-source federated data infrastructure, which enables stakeholders to consolidate and connect relevant data sources, models and information products across DRM and CCA application domains and institutional operating systems and languages, see more in Schröter et al. [16].

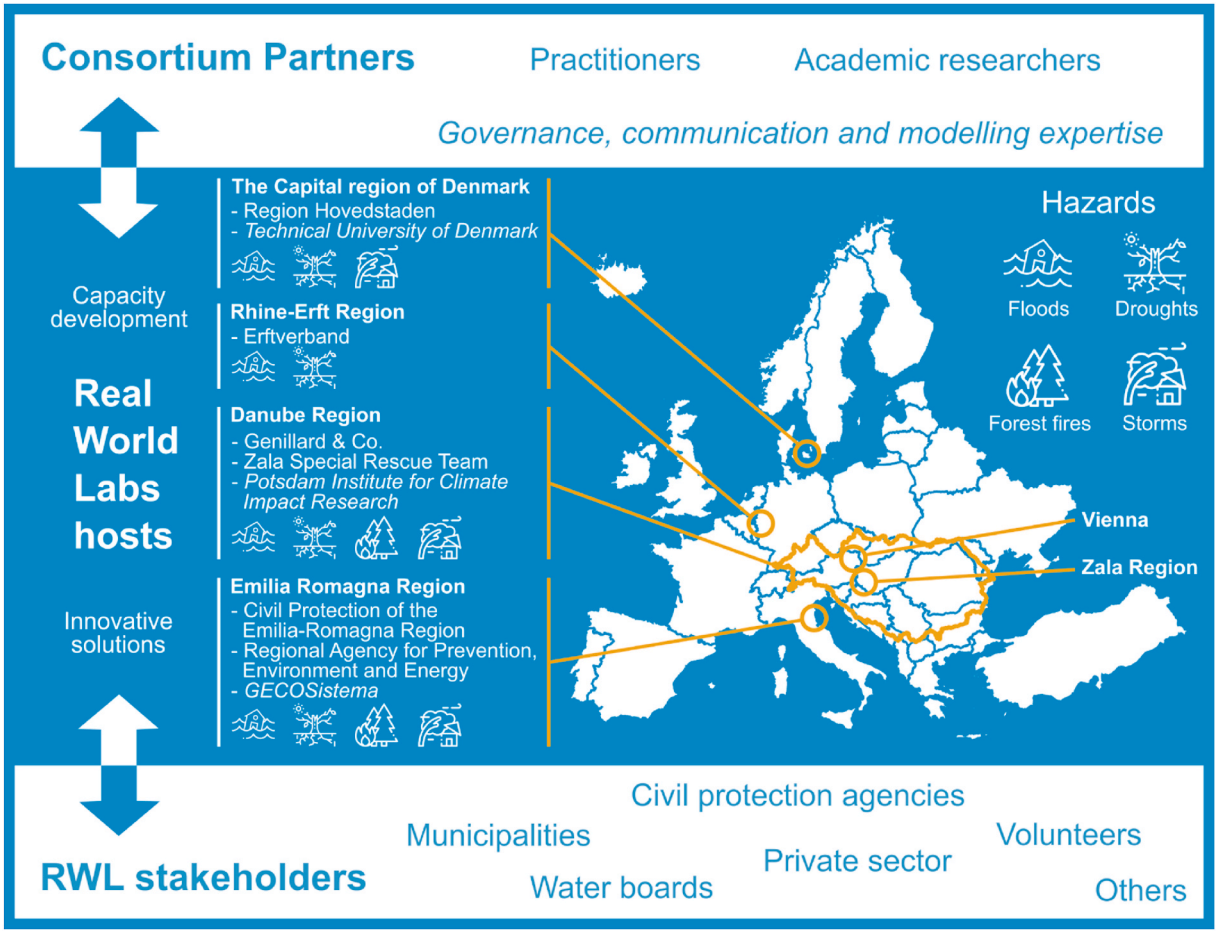


Fig. 1. Overview of Real World Lab hosts, stakeholders, hazards and supporting consortium partners.

models or tools for specific hazards. An overview of the project partners, each RWL, the stakeholders involved, RWL activities and interactions with partners (between November 2022 and July 2024) can be found in Supplementary Material A.

For the academic researcher, knowledge co-production in this context differs from traditional research development and offers an opportunity to build capacity through direct involvement in the process. The goal is both to learn from and gain new research ideas, as well as to support the RWL by sharing knowledge and developing methods and applications that address current stakeholder challenges. By working with practitioners, academic researchers can learn about stakeholders' real-world problems, iteratively adapt initial research premises and deliver a targeted dissemination of relevant insights. Rather than starting with academic sources like literature reviews and producing outcomes that may be overlooked by non-academic communities, the process begins by identifying the RWL's specific needs. Tools and knowledge are introduced to spark discussions and stimulate knowledge exchange focusing on achievable developments. Facilitated by the RWL practitioner hosts through workshops, this approach shifts to an iterative, stakeholder-guided process. This two-way exchange between practitioners and academic researchers places additional responsibility on both to actively engage with one another, by sharing their time and expertise, so each side can benefit from co-produced outcomes. The emphasis is on practical and meaningful two-way exchange and collaboration between practitioners and academic researchers [46,47], using existing tools and research to create relevant, locally owned applications embedded in DRM and CCA policy and practice [18,40].

2.2. Approach to knowledge co-production and capacity development

The Risk-Tandem Framework, developed in the DIRECTED project, uses knowledge co-production to support risk governance toward enhanced DRM and CCA solutions [45]. The operationalisation of the knowledge co-production by RWL hosts within the Risk-Tandem Framework is supported and structured by the Tandem Framework [12,21], which guides the capacity development. The Tandem Framework provides a structured process for facilitating knowledge co-production, recognising that knowledge co-production is both a research and design process. Firstly, the Tandem Framework must be carefully adapted to the specific context in which it is applied. It can then be followed, adopting a transdisciplinary learning-by-doing approach, enabling both practitioners (acting as

facilitators) and academic researchers to develop the capacities needed for co-designing risk governance interventions. The capacity development programme is context-driven [22,25,48], designed in response to the needs of the RWL hosts, and, guided by the premise of triple-loop learning [32,49]. Triple-loop learning goes beyond "standard" learning by providing opportunities for feedback, learning and change through questioning the premise of working [49], while avoiding top down knowledge transfer to support more transformative learning [50]. Within the RWLs capacity development aims to support RWL hosts (practitioners) to co-design (with the consortium academic researchers) the co-production process, using interactive and engaging methods that build trust and stimulate more meaningful interactions among stakeholders [22]. This supports the emergence of innovative, creative and multifaceted perspectives, a common understanding of shared challenges, and the potential identification of solutions for complex governance issues [51]. The approach aims to support non-hierarchical, equitable relationships between learners and trainers, and across science and practice that redress power imbalances, and allow for openness, trust and flexibility to adapt to different contextual needs [46,47].

The co-production process in our RWLs involves different actors and knowledge types and thus requires the development of a range of capacities and skills, among practitioners, and the academic researchers involved. Based on scoping consultation interviews with RWL hosts, general and targeted training and support activities were developed to respond to emerging needs and support knowledge co-production in each RWL (see further details in Supplementary Material B). This involved a blended and dynamic approach mixing interactive online and in-person workshops, guidance materials and one-on-one support consultations. In efforts to cultivate a robust evidence base that supports replication [23] and evaluate the quality of the capacity development, we combine good principles for knowledge co-production [22,47] to identify indicators that value both processes and outcomes [52]. However, this alone is inadequate for explaining how and why capacity development contributed toward successes (or shortfalls) in co-production. As such, monitoring and evaluation are embedded within the capacity development approach to inform the knowledge co-production process based on emerging evidence and needs.

2.3. Capacity and skills data collection and analysis

In this paper we reflect on the capacity development activities and outcomes which aimed to support RWLs hosts on their knowledge co-production journey within the first period of the DIRECTED project (November 2022 to July 2024). Capacity and training needs assessed through continuous scoping consultation interviews, informed the development of the initial training resources and dedicated activities (see details of training and guidance developed in Supplementary Material B). When needed, additional support consultations were conducted ahead of RWL workshops where tailored support and guidance was provided to design workshop methods, conduct research or build confidence in facilitation. Data on the development of RWL practitioners' capacity was collected after each RWL multi-stakeholder workshop where RWL hosts participated in a debrief interview with 'trainers' and completed self-reflection evaluation forms to collect feedback on their experiences, capacity development and any emerging needs. Fig. 2 presents an overview of the approach to monitoring and evaluation of knowledge co-production capacity development. Themes covered in the debriefing interviews and evaluation forms included reflections on what worked and what didn't (e.g. facilitation skills, interactive methods), how to learn and adapt for future interactions (e.g. expanding stakeholder participation, embedding evaluation, conducting more research) and highlighting the support and capacity development needed from academic research partners. Online meetings were recorded and transcribed using Microsoft Teams. RWL hosts also shared workshop agendas, photos, and meeting reports for additional analysis. This qualitative data was analysed using an open and inductive approach to coding [53] to capture key relevant evidence related to emerging capacities and skills being demonstrated and associated needs. This data was collected at various points for each RWL depending on their progress in engaging stakeholders and organising workshops and their requests for support (see details of interactions per RWL in Supplementary Material A). This is a continuous engagement process between the academic researchers (trainers) and the RWL hosts, which informs the local co-production process and the wider training activities for all RWL hosts. Future activities are being designed to elicit needs based on emerging demand through a capacity needs assessment to inform

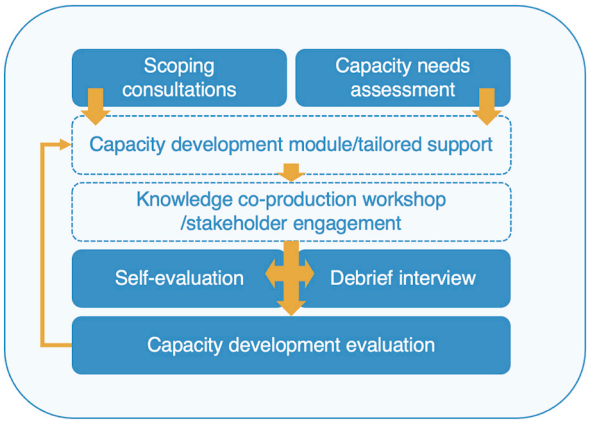


Fig. 2. Approach to monitoring and evaluation of knowledge co-production capacity development in the RWLs.

capacity development support and activities for RWLs.

The RWL workshops were facilitated by RWL hosts including their technical partners where applicable and were not typically attended by the wider academic researcher partners (including trainers). However, the level of input by the partners could be adjusted to the needs and capacities of the respective hosts. For example, support was requested during one online meeting to present the technical details of the Data Fabric to the stakeholders in the Rhine-Erft RWL. It is foreseen that this request for support will increase as the co-design process continues and RWL can benefit from additional knowledge from academic researchers, and direct support from trainers when needed. Additionally, enabling participation of researchers in workshops allows for further observation and reflection on the capacity development. As the RWL host practitioners are leading the design, research and facilitation of knowledge co-production activities, practitioners from each RWL were offered the opportunity to co-author this research article and contribute to its writing and review. Without their participation, the research on their capacity and skills development would not be possible. Furthermore, the academic researchers (including modelling teams) within the consortium involved in supporting the development of training materials and workshop design (sharing expertise and tools related to data/modelling, information, communication and governance) are also involved in writing this article, with a specific role in reflecting on their own capacity development through the process.

3. Developing knowledge co-production capacities and skills

In the RWL context, practitioner hosts - ranging from local/regional authorities to emergency responders and technical support partners — broker knowledge to bridge scientific insights with (operational) decision-making. However, the skills required among practitioners and researchers to enable such knowledge co-production are rarely discussed in detail [52]. Using the Tandem Framework [12] and insights from its previous applications as a starting point [21], in combination with a review of literature and emerging insights from RWL hosts' application of training and guidance provided, a list of knowledge co-production capacities and related skills has been established, indicating how these enable knowledge co-production principles (Table 1). Here we distinguish four core capacities. Firstly, collaborative capacity is an overarching capacity that is fundamental for initiating, maintaining and sustaining a transdisciplinary knowledge co-production process to achieve desired outcomes. In addition, systems thinking capacity, creative capacity and reflexive capacity are identified for enabling or guiding facilitation, design and research within co-production processes and outcomes. Building on the work of [54] we recognise the blurred role of researchers, practitioners and designers interwoven in transdisciplinary processes, thus target the development of design, research and facilitation skills for capacity development, as outlined in Table 1. Different capacities and related skills support RWL hosts in implementing different phases of the Tandem Framework [21] i.e. 1) scoping and review, 2) co-exploration, 3) co-design, and 4) integrating new knowledge and partners - along their knowledge co-production journey. These capacities also support various good practice principles [47,55] including those of context-based, pluralistic, goal-orientated and interactive co-production [22].

We outline how the development of these capacities, through building skills for designing, researching and facilitating methods in the RWLs, are targeted through specific capacity development activities and resources (e.g. guidance notes, online or in-person

Table 1
Knowledge co-production capacities and skills and supported co-production principles.

Capacities	Skills	Principles	Literature
Collaborative capacity	Design: collaborative engagement mechanism for selecting and involving transdisciplinary stakeholders, and create an enabling open, safe/neutral and respectful space (e.g. in Real World Lab). Research: mapping stakeholders and their priorities, interests and needs. Facilitate: participatory and inclusive methods towards a common goal and ensure all voices are heard and contribute meaningfully. Facilitation that surfaces and navigates tensions in ways that feel safe for all participants.	Plurality/ transdisciplinary Goal orientated Non-hierarchical Safe, neutral and respectful	[12,21,22,47,55,57–59]
Systems thinking capacity	Design: methods and tools to explore systems interactions, dependencies and uncertainties (e.g. storylines, systems mapping, user stories, visioning). Research: to understand governance context, systemic issues/underlying drivers and critical gaps/problems. Facilitate: methods to understand system complexity and uncertainty, break it down and identify leverage points for change.	Context based Influences change	[13,22,25,47,48,57,65–68]
Creative capacity	Design: interactive engagement approaches to support experimentation and innovation, and creative methods that build curiosity and empathy. e.g. (serious) games, simulations, narratives, prototyping. Research: new opportunities, partnerships, and resources to support innovative and creative practices. Facilitate: creative and artistic methods to support knowledge exchange, experimentation and emotional understanding (e.g. sensemaking, envisioning exercises, solution mapping).	Interactive Experimental Empathetic	[12,22,47,69,72–74,77–79, 81,82]
Reflexive capacity	Design: reflective methods that support evaluation and learning during workshops/activities to guide iteration. Research: critically reflect on the engagement process and progress (own values, emotions, assumptions, power dynamics). Facilitate: reflection and mutual learning activities with stakeholders to adapt future activities.	Plurality/ transdisciplinary Iterative	([21,46,47,58,84]; McGregor, 2017; [22,50,52,72,83,85])

training), see further details in Supplementary Material B. Many of the capacities and skills outlined in Table 1, and described in the following paragraphs, are also applicable for the academic researchers who support RWL practitioners in enabling co-production especially during co-exploration and co-design phases. Here we argue that these skills primarily need development by those who are leading and coordinating the RWL activities i.e. RWL host practitioners, and the project's capacity development effort targeted this group [41]. However, such capacities and skills will naturally develop and emerge within other researchers supporting the RWL activities and those participating, through learning-by-doing, and is further reflected on in Section 4.2. The presented capacities and skills should not be considered final and exhaustive. Rather, they are revised continuously through engagement with stakeholders, as more practitioner and academic researcher capacities and needs emerge during the iterative application of the co-production process.

3.1. Collaborative capacity

Collaborative capacity is important to initiate and sustain transdisciplinary, pluralistic and goal-oriented knowledge co-production processes [22]. Doing so builds a foundation of design, research and facilitation skills to understand the context, engage stakeholders and understand perspectives, which interlink with systems-thinking, creative and reflexive capacities. Conscious facilitation [55] in particular, requires skills enabling different worldviews to be valued and heard. Balancing different interests and goals across and between users and producers of knowledge requires skills to manage expectations and incentives at the outset [56], and support negotiation and conflict management to achieve joint outcomes [12,22]. Building these skills can ensure a non-hierarchical knowledge co-production process [47], while creating institutional space for co-production [57] that feels enabling, safe, neutral and respectful [58]. Navigating the transdisciplinary journey of scoping, distilling, integrating and using relevant local and scientific knowledge from across scales and disciplines [21] requires skills around convening, listening and translating information [59].

Additionally, there is increasing emphasis on the role and capacities of scientists and modellers (academic researchers) collaborating in co-production processes highlighting the need for: empathy with regards to the diverse 'lived experiences' of stakeholders [47]; distillation and translation of disaster or climate risk information using multiple lines of evidence, such as storylines [60]; accountability for the information produced [13,61,62]; and, transparency through the communication of confidence and uncertainty [63,64]. Building collaborative capacity should enable practitioners and academic researchers to embark on new ways of working and sustain collaboration beyond the status quo [22].

To support collaborative capacity development, a guidance note and mapping exercises on stakeholder engagement was provided to support RWL hosts in thinking about who to engage in their RWL – encouraging a broad range of actors across the science-society interface and a broad range of knowledge types. To support purposeful workshop organisation and relationship building, a guidance note was provided on interactive workshop design and facilitation including templates for group activities, icebreakers and evaluation. See further details in Supplementary Material B.

3.2. Systems thinking capacity

Systems thinking supports an understanding of complex systems and identifying leverage points to intervene for sustainability [65]. Systems thinking competence is defined by (Wiek et al. [66], p. 207) as "the ability to collectively analyse complex systems across different domains (society, environment, economy, etc.) and across different scales (local to global), thereby considering cascading effects, inertia, feedback loops and other systemic features related to sustainability issues and sustainability problem-solving frameworks." Building capacity to combine systemic risk analysis with knowledge co-production processes locally can build a deeper understanding of complex systems, interdependencies and related interventions [67]. A key principle, and subsequent skill for knowledge co-production is 'big picture thinking' [47] because it can help in understanding the added value of data and information in the context of a wide set of multi-sectoral challenges as well as understanding what this means at a local level. Future visioning or 'storylines' [68] can help build skills to co-explore the interaction of different stressors when there is inherent uncertainty in model data. Developing skills to use methods like climate risk narratives and development pathways (linking current with past and future) [13,47] can build capacity for systems thinking. Practitioners and researchers should be able to leverage the co-production process toward identifying where their work will have the most impact in their context [57], to influence change in DRM/CCA policy and practice. Although not necessarily a quantifiable skill, it can be cultivated via systems thinking activities that are open to transformative ideas (even if deemed unfeasible), capable of contesting the status quo. Building research skills will enable a wider understanding of the governance context (issues, drivers and gaps) to identify leverage points for systems change, while contextually grounding the co-production outcomes [22,25,48].

Training around systems thinking involved training online and in-person to develop design and facilitation skills among RWL practitioners. This included practical exercises and tools for risk scoping to establish preliminary boundary conditions for risk management with local stakeholders beyond hazards themselves, mapping of context and the development of 'user stories' to explore different types of vulnerability. Exploring systemic risk was exemplified through a practical, creative exercise emphasising the interconnectedness of hazards, socio-economic stressors and dynamic vulnerability in a climate change context. Training for the consideration and assessment of other complex factors which can define risk such as distinct types of vulnerability, gender equality and social inclusion have also been provided. Training around the development of 'storylines', scenario games, and future visioning exercises help to explore common terminology, complexity and uncertainty. To support *research skills* development, guidance notes on group interviews and risk governance guiding questions were developed for RWL hosts, alongside tailored support reviewing different research tools. Supporting systems thinking capacity development, RWL hosts used the guidance to develop their own research tools specific to their needs and context to collect relevant governance, communication and data/modelling systems information from their

RWL. See further details in Supplementary Material B.

3.3. Creative capacity

Here creative capacity is understood as having the skills to design, research and/or facilitate creative methods, tools and collaboration that encourage interactivity and experimentation, while building empathy within transdisciplinary knowledge co-production processes. Increasingly DRM and CCA stakeholders are encouraged to participate in 'serious games' to explore role play, multiple hazards and decision-making for fictitious, yet realistic scenarios [69,70]. Many DRM organisations will already have experience with training exercises or simulations that present disaster scenarios in real-world or virtual environments [71]. Such experiences can build a wider understanding of empathy and emotion in decision-making [72], a key principle of co-production [47]. Interactive and creative methods can help open dialogue to build relationships, understand complex issues and stimulate new ideas [73,74] and support an inclusive approach [75] in transdisciplinary learning spaces [76]. Examples of imaginative and creative practices in DRM/CCA include storytelling workshops around drought impacts [77], imaginative framing of climate futures [78], using acrobatics and humour in policy dialogues [79] and play using LEGO to support children's participation [80]. Prototyping is a participatory method used in co-design [81] which can support experimenting, refining and negotiating technical products or services. Building skills to apply more creative and interactive methods and tools during knowledge co-production is important [12,22] to support experimentation in RWLs [82]. Research skills help in mapping and exploring new collaborations e.g. with artists/creative practitioners to access support in design and facilitation.

Training to strengthen creative capacity included an in-person Risk-Tandem workshop in Cologne (September 2023) involving playing the Breaking the Silos Game [69]. The game helped to simulate the complexity of decision-making in a multi-hazard, multi-actor setting (underpinned by competing interests, limited funding, and uncertainty) and highlighted the tense and pressurised situation for decision-making. This aimed to build the foundation for developing a tailored approach to co-designing interdisciplinary serious games or exercises for risk governance during DIRECTED. The training also included experiences using creative and play-based materials and being part of a World Café. The training aimed to build confidence in designing and facilitating creative methods and inspire creative thinking towards RWL workshop design, including for citizen engagement. See further details in Supplementary Material B.

3.4. Reflexive capacity

Reflexive capacity is needed to ensure inclusion and plurality within the transdisciplinary collaboration, while providing space to reflect on the stakeholders involved, and the goal and methods used to stimulate critical observation, encourage iterative loops, and identify pathways to improve and adapt. Polk ([83], p. 114) defines reflexivity in transdisciplinary co-production as "on-going scrutiny of the choices that are made when identifying and integrating diverse values, priorities, worldviews, expertise and knowledge". Individual and group reflexivity supports knowledge integration that recognises different knowledge sources and perspectives and creates common understandings [83,84] including among academic researchers with an openness to take on new ideas [84]. Building reflexive capacity can help practitioners question and interrogate assumptions around knowledge production [72]. Critical reflection can enable transformative learning, by challenging our own ideas and beliefs, and those of others [85], helping to move away from established ways of thinking and solving problems [50]. Collaborative reflexivity improves the integration and synthesis of both academic and real-world contributions and perspectives, generating useful transdisciplinary knowledge to reach shared goals [90]. Building capacity for reflexivity will help enable stakeholders to remain open to learning through their engagement and co-production journey [22]. Monitoring and evaluation are essential for iteratively applying knowledge co-production processes, as learnings from its implementation should inform its future directions [21,52]. Building reflexive research skills of practitioners to be able to confidently conduct surveys, focus group discussions or interviews is important as part of scoping their activities [58], and can help stimulate embedded, reflective and critical research that captures contextual dynamics, challenges and opportunities [47].

Reflexive capacity was cultivated through the project by creating relationships between the practitioners and the academics through the training activities and wider consortium activities. Key critical reflection moments were after each RWL workshop (in debriefs and self-reflection forms) where trainers and practitioners can comfortably share learning and observations, while being supported to take next steps to adapt plans or activities. RWL practitioners were provided with sample questions to embed participant reflections within workshops, and were encouraged during support consultations to facilitate evaluation methods and reflective conversations to encourage mutual learning and flexibility to adapt plans or interventions. An online module on monitoring and learning was also provided to RWL hosts. See further details in Supplementary Material B.

4. Results and discussion

4.1. RWL insights and learning

Here we highlight some specific demonstrations and learning around capacities from RWL practitioner hosts for knowledge co-production in the different RWL contexts. We also reflect on the challenges and lessons for capacity development to build the associated skills for knowledge co-production.

4.1.1. Collaborative capacity

Overall, RWL practitioner hosts demonstrated skills to establish their multi-stakeholder RWLs using the guidance tools provided to research and map out different stakeholders to engage. Typically, stakeholders formalised their support for the RWL through Letters of Engagement but in some cases, this was not possible. Some RWLs faced more challenges than others in designing and facilitating interactions in their RWLs, given the different starting points for engagement and previous experience. The Capital Region of Denmark RWL focused on strengthening transdisciplinary collaboration between emergency management agencies, municipalities and other relevant actors in the Roskilde Fjord area exposed to coastal and riverine flooding, cloud bursts and storms. These actors typically have limited interactions around joint planning across geographic or administrative borders, and there is a sharp distinction between DRM and CCA activities. RWL hosts designed the first workshop (March 2023) using guidance and support provided, and were satisfied with their facilitation skills but recognized that more could have been done to create a balanced discussion between the interests of emergency management actors and municipalities, whose primary concern is CCA, as the workshop design steered conversations towards emergency management.

The Emilia-Romagna RWL had strong preexisting relationships that enabled the collaboration in the RWL. After feeling motivated by the game-based training (September 2024) combined with growing interest from RWL stakeholders emerging around conducting a real-exercise with simulated flood events, the RWL designed and facilitated a Flood Exercise in Rimini in June 2024. The exercises demonstrated the collaborative capacity of the RWL hosts to bring together authorities, volunteers and citizens, and highlight potential to improve early warning, data and modelling tools for DRR, and communication with citizens and situational volunteers. Reflecting on the exercise, the hosts shared how implementing this type of collaborative exercise would not be prioritised without the RWL set up



Fig. 3. Impressions of the first Emilia-Romagna Region RWL workshop in March 2023 (see top image a.) and the 2nd workshop in September 2023 using knowledge co-production engagement methods and outputs (see bottom images b. and c.).

in the project. The Emilia-Romagna RWL progressed furthest towards citizen engagement in their RWL given their strong volunteer network, however, other RWLs prioritised building inter-professional relationships between DRM/CCA agencies. To achieve true transdisciplinary collaboration that involves citizens in knowledge co-production [22], it is evident that many RWL hosts require a more staged approach to strengthen two-way risk communication [86], to carefully navigate institutional mandates (e.g. in Rhine-Erft RWL) and identify citizen engagement entry points that can be sustained. RWLs create an enabling environment where future initiatives can integrate community perspectives into the co-production process.

The Danube RWL, hosted by reinsurer Genillard & Co., experienced challenges to engage with public sector authorities in Vienna, and instead of organising multi-stakeholder workshops, prioritised engagement in relevant conferences and events to meet with Danube and European level stakeholders (e.g. Joint Research Centre, Viadonau). In the sub-RWL in Zala, the host, Zala Special Rescue Team, has an extensive network with regional and local stakeholders across public administration, scientific, advocacy and civil society organisations in the region, creating a strong base for transdisciplinary collaborations, and was able to formalise their support via Letters of Engagement. However, they struggled to initiate multi-stakeholder workshops given the cultural norms, and instead focused on bilateral discussions within their network, to understand the gaps and needs around data/modelling, communication and governance for DRM and CCA. Overall targeted support and guidance for the Danube RWL sub-hosts was provided similarly to the other RWL, however, this was slower to be taken up and utilised given the challenges around engagement and finding a clear focus/priority in each sub-RWL. Looking ahead, both sub-labs are planning their first co-production workshop with a more streamlined group of stakeholders to co-explore and co-design solutions to meet their needs and are more actively engaging in support consultations. This reflects a challenge identified across the RWLs, around the limited time and capacity of the RWL hosts and their stakeholders, as similarly recognized in other RWL settings [37,82]. There is a trade-off between resources available and goals (or expectations) of the transdisciplinary collaborative process for building awareness and action for jointly managing risks. Building collaborative capacity among practitioners and researchers for knowledge co-production stimulates this process but what it can achieve will depend on the time availability and commitment/motivation of those involved.

4.1.2. Systems thinking capacity

Systems thinking capacity was demonstrated in multiple RWLs through their approach to research and workshop design and facilitation which applied the guidance provided. The Rhine-Erft RWL demonstrated research skills to support systems thinking, by developing a questionnaire for the district stakeholders to capture challenges for risk governance and communication, share experiences of the 2021 flood, and collect suggestions for changes needed in governance structures, and guidance for the RWL development (April 2023). This then informed the design of the next in-person workshop (June 2023) to facilitate a discussion around the results and priorities. The Danube sub-RWL in Vienna and Capital Region of Denmark RWL also designed questionnaires for their stakeholders to understand the governance context and inform RWL activities.

The Emilia-Romagna RWL designed a workshop (September 2023) embracing systems thinking after receiving the training on exploring complex risk (May 2023, online) and creative methods training (September 2023, in-person). Fig. 3 highlights the differences between the first and second workshops in the Emilia-Romagna RWL, demonstrating the development of workshop design and facilitation skills. The RWL hosts were very satisfied with their capacity to facilitate the workshop using a World Café style group interactions indicating, *"The discussion went very well. We were able to collect a lot more information, starting with our own questions but then evolved more than expected"*. The benefit of systems thinking and transdisciplinary collaboration that emerged from the first workshop was identified by hosts. For example, the Hera Group (municipality owned companies) sensor network data is not accessible to the municipality of Rimini or Emilia-Romagna Civil Protection, and that there is no exchange between the ARPAE and Civil Protection sensor network with the Hera Group network. The RWL hosts identified this as a leverage point to influence and planned a follow up discussion to see how to work together. Building systems thinking capacity, helps practitioners and academic researchers identify new opportunities (e.g. multi-risk, technology) and highlights challenges (e.g. identifying risk drivers) for improving communication, data/modelling and/or governance, however, some priorities may be out of the scope of the RWL activities in the DIRECTED project.

Taking a systems perspective toward risk management involves many different actors with varied goals, capacities, knowledge and concerns pursuing multiple activities and interacting in different ways with one another [87]. As supporting academic researchers, a conscious choice was made to allow the RWL hosts to develop their regional RWL in their own way to work within the bounds of the existing cultural, political, institutional and technological boundaries, to ground the process contextually [22,25,48]. This allowed practitioners to build systems thinking capacity, by finding their own leverage points for scoping risks and engaging stakeholders and navigate their deeply embedded methods of engagement towards co-production. Each RWL evolved differently, and despite some delays and sometimes an unstructured approach to engagement, this 'hands off' approach was deemed necessary to create a truly locally or regionally led knowledge co-production process.

4.1.3. Creative capacity

Different RWLs demonstrated different levels of skills towards building creative capacity. In the Capital Region of Denmark RWL hosts demonstrated existing skills and willingness to design and facilitate interactive methods (namely World Café) during the first RWL workshop (March 2023), along with support and guidance provided. This was reflected by the stakeholders, who in turn endorsed future CCA and DRM simulations as a tool (one stakeholder even provided a concept note for this purpose). This was not the case in other RWLs whose skills notably evolved after specific training activities. In the Rhine-Erft RWL, initial RWL workshops followed a typical formal pattern as inter-organisational meetings. There was a concern amongst most hosts that creating unfamiliar levels of interaction, or creative methods could make participants uncomfortable and risk reducing their participation. A RWL meeting in

November 2023 opened up the possibility to have a simulation exercise (or game) as part of the RWL activities. Working with the RWL hosts during the game-based and creative co-exploration training (September 2023), a seed of interest was planted with the RWLs and their willingness to explore these approaches grew. On a personal level, one Rhine-Erft RWL host felt that the creative activity during the training helped them to break down the formal communication barrier and share ideas in a tactile way indicating that "*I feel like this could work in our RWL to break down the formal roles of the stakeholders.*" As a stepping stone towards the simulation, the hosts demonstrated creative capacity by deciding to design a workshop using creative and interactive methods (March 2024) to map out communication flows across stakeholders for an imminent or actual flooding which drew on experiences on the 2021 flooding, using a more systems thinking approach. Fig. 4 gives an impression of the training exercise (a.) and the interactive RWL workshop (b.). Reflecting on the workshop, the RWL host indicated they were very satisfied with their ability to generate a comfortable environment for participants, and their listening skills, which was supported by the creative methods. Additionally, they identified the value of the methods for improving dialogue and stimulating interest among stakeholders, while being committed to continue to use and experiment with creative methods in their RWL.

The different cultural contexts of organisations and their multi-stakeholder settings were found to have an influence on practitioners' confidence to apply creative methods. For example, the perception of the RWL hosts of the creative process and whether they perceived if this would be embraced or resisted by their RWL stakeholders played a role. The experience described in the Emilia-Romagna and Rhine-Erft RWLs which started with more formalised engagement and moved toward creative and interactive methods, demonstrates the time that is needed to open mindsets and overcome the concerns of practitioners. To enable creative capacity among practitioners and academic researchers, targeted support, learning exchange and encouragement from others is needed, especially from researchers and practitioners who have travelled similar journeys to overcome fears and concerns. This can help to build trust and a willingness to experiment with new approaches and methods in the RWL [44]. Expectations should be managed not to overwhelm practitioners with new creative or interactive methods but to gradually encourage the shift in thinking beyond existing methods of engagement. However, once confidence is established, the potential to apply a wider range of creative and experimental methods opens, which will be beneficial for the RWL co-design of the technical tools (Data-Fabric) and governance mechanisms in DIRECTED.

4.1.4. Reflexive capacity

RWL hosts demonstrated growing levels of reflexive capacity at different stages during this period of their RWL implementation, however, this is expected to evolve further towards the end of the project which demands more iterative interactions and reflections to progress solutions in their RWL. In the Capital Region of Denmark, a challenge was the staff turnover of RWL hosts, which resulted in a gap of engagement and follow up after the first workshop and patchy attendance at different knowledge co-production training activities. This also meant that the new RWL hosts, despite having access to a report on the first workshop, did not have the personal experience with the stakeholders to really understand the challenges and needs that the project could address. Likewise, the new RWL hosts had quite different professional backgrounds than their predecessors, who are trained anthropologists. To overcome this, the RWL hosts demonstrated research skills to support reflexivity, recognising the need to adapt plans and reaffirm relationships the RWL hosts by organising four group interviews between municipalities and emergency management agencies with overlapping jurisdictional boundaries. Their idea was to use the group interviews to inform the next in-person knowledge co-production workshop. This approach proved beneficial for improving the hosts research skills and understanding of the problems and needs in different agencies

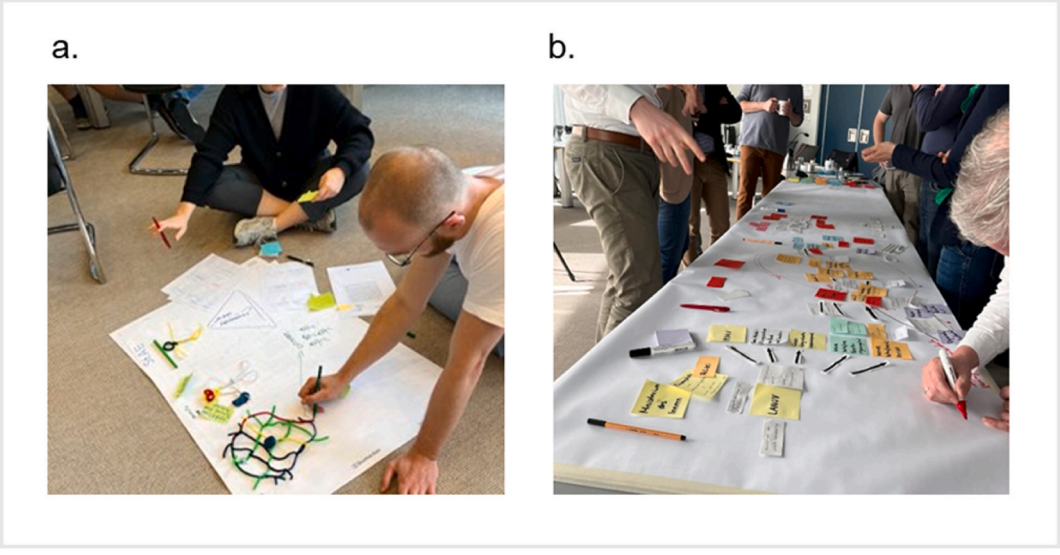


Fig. 4. Impressions from the Rhine-Erft RWL hosts engaging in the co-exploration training (see image a. on the left) and the knowledge co-production workshop in March 2024 with their RWL stakeholders mapping communication flows and procedures.

(systems thinking capacity) and building relationships and skills to stimulate dialogue towards shared goals (collaborative capacity).

RWL hosts needed to demonstrate reflexivity in how they prioritised the goals of their RWL. For example, through ongoing interactions in the Rhine Erft RWL, they collectively prioritised working towards governance and communication solutions over modelling tools, which informed the workshop design. Individual reflexivity was identified in the Rhine-Erft RWL, where one host critically reflected on the stakeholder interactions during the workshop, recognising that stakeholders held back in sharing their bilateral/group conversations in full in plenary. As successful as the event was at building a creative environment for open sharing of knowledge, the hosts reflected disappointment in their facilitation skills to capture specific stakeholder insights, *"Stakeholders were interested and engaged during the workshop and gave positive feedback, but I felt like I didn't collect all the relevant information from the group members."* This potentially demonstrates some ambiguity around responsibilities among stakeholders and/or fear of attributing blame to others, and desire to avoid tension or conflict. As such, this identifies the need to build RWL hosts skills to facilitate open reflection during workshops and mutual learning to guide future activities. Although training was provided to RWL hosts on monitoring and learning in their RWL, such specific insights can guide future training.

4.2. Reflections on capacities among academic researchers supporting RWL knowledge co-production

Although the capacity development activities targeted the RWL practitioner hosts, the process of supporting them provides scope to reflect on how these capacities are developing for the academic researcher partners. Here we share initial insights, which are expected to further develop going forward in the project.

4.2.1. Collaborative capacity

The RWLs provided academic researchers access to real-world insights across four different regions in Europe, providing an opportunity to learn about how to make concepts, frameworks and risk modelling/analysis tools more practical and useable by local stakeholders, in different contexts. Academic researchers, especially modellers, built capacity to recognise the diverse needs and perspectives across four geographically and culturally diverse RWLs and integrate their converging needs into the model and tool development. Furthermore, modellers realized how crucial a two-way interaction in the design process is. Setting up the modelling tasks and gathering data to address the RWLs needs, simultaneously requires a significant information translation effort from the modellers, and a willingness in RWLs to identify needs that may be addressed by models, together with a commitment to provide existing data and knowledge. Another benefit of interactions between academic researchers and RWLs is how ideas from one RWL can inspire discussions and innovations in others, building collaborative capacity. For example, during the Rhine-Erft RWL engagement during a consortium meeting, the Erftverband showcased post-2021 flood measures, prompting questions about the potential impact if these measures had been in place at the time of the event, and whether a cost-benefit analysis could be conducted by simulating this single event with and without the measures. This sparked further ideas related to "forensic analysis" in the context of adaptation appraisal to embed within future knowledge co-production workshops. Starting in the Rhine-Erft RWL, these discussions then led to further exploration of these ideas between modellers/scientists and RWL hosts in the Capital Region of Denmark RWL, demonstrating a ripple effect across RWLs. Overall, the RWL and project set-up facilitates this collaborative space where practitioners and academic partners stimulate exchange of ideas and knowledge brokering [12,21,88] both at the regional and project level, supporting capacity development for knowledge co-production. As we move towards the co-exploration and co-design phases of the knowledge co-production process, the academic research partners will play a more central role in co-producing integrated technical and governance solutions with the RWLs.

4.2.2. Systems thinking capacity

Creating a two-way learning environment between practitioners and academic researchers within the consortium is important to openly access and share different knowledge and expertise, while each role can leverage their specific needs and complement existing skills and capacities. Academic researchers need to dedicate time proactively identifying entry points to support practitioners in design, facilitation and research activities in the RWL by listening to their needs and priorities. Subsequently, this real-world knowledge can inform the development of governance and modelling frameworks and tools led by academic research partners. As such, systems thinking capacity is equally needed by both practitioners and academic researchers, who need to work together to understand the problem and identify solutions that can be sustained. However, for academic researchers not based in the local/regional context, it takes more time to develop these relationships and identify what support is best matched. The set-up of the RWLs with technical support partners proved to be particularly useful for building systems thinking capacity among the academic researchers in the case of the Capital Region of Denmark (with DTU) and the Emilia-Romagna region (with GECOsistema). Technical support partners shared their specific expertise around locally relevant risk-related data, models and tools and experience in other projects/applications and supported RWLs hosts with limited technical knowledge on risk. These partners built close relationships with the RWL practitioners and were able to leverage scientific and governance knowledge and experience working on DRM/CCA in the local and regional context, supporting systems thinking and leveraging change. Strengthening these relationships between academic researchers and practitioners, especially in the local/regional context, has potential to influence systems change, as they can likely be sustained beyond the project through other initiatives. This can also help motivate and empower future trandisciplinarians [32,33] in practice and academia because they can envision the wider impact and work to protect existing spaces for knowledge co-production, advocate for resources and articulate the benefits, to enable continued collaborative structures and mindsets [57]. However, as identified in Denmark, governance arrangements can discourage systems thinking, where the municipalities have absolute authority on CCA and DRM without a formal regional decision-maker or mediator [89], making it difficult to build systems thinking capacity

under such constraining conditions.

4.2.3. Creative capacity

Creative capacity was strong within the trainers who had confidence and experience in using such methods to stimulate knowledge exchange, with a similar openness noted by other supporting academic researchers who were not familiar with such methods. Moving forward academic researchers with design-thinking and engagement backgrounds, where necessary plan to assist directly supporting RWL hosts to build confidence and support experimentation in workshops. While this in turn will strengthen the creative capacity of academic researchers grounding their methods in context. Furthermore, academic researchers can help identify additional collaborations and resources to support RWL hosts in designing and facilitating creative methods for specific audiences, for example working with local artists or communication specialists, which is being explored in the Rhine-Eft and Emilia-Romagna RWLs.

As the RWLs co-design technical and governance solutions in their RWLs, this is expected to advance the creative (and systems thinking) capacity of modellers to explore new ways of embedding modelling results and tools (via the Data Fabric) into interactive workshops e.g. using storylines, narrative and role play exercises. Academic researchers working on risk modelling, identified challenges to visualize and communicate results effectively to stakeholders. For example, how to visualize complex results of cascading hazard impacts to increase understanding of the complexities involved within the modelling realm and potential usefulness for the decision makers on the ground were especially challenging. The use of climate storylines [68] and the positioning of these within risk-based modelling approaches [67], including the complex risk landscape they are involved, needed new ways of thinking among the academic researchers how to communicate and present such results. This is not only modelling related but also was found in regard to the data needs for upscaling results to different spatial levels as well as across sectors, decision makers, and governance processes, making it essential for a more creative approach for the Data Fabric to align with potential users.

4.2.4. Reflexive capacity

From the perspective of the academic researchers who developed the RWL training, the targeted capacity development approach combining support consultations and in-person and online workshops was found to be a useful approach to build capacity and skills that responded to their needs. This allowed the academic researchers to have open communication lines to continuously understand how co-production can be utilised and ingrained into their localised processes and have open conversations about the barriers and opportunities along the way. This exchange also facilitated discussions around adapting workshops to use locally appropriate terminology and language that can be understood by stakeholders. The self-reflection sheets allowed the hosts to think about their facilitation skills and what could have improved during the workshops/activities which allowed the academic researchers to brainstorm and co-explore solutions and next steps. This demonstrates the importance of continuing the monitoring, learning and evaluation process to document the outcomes of the co-production process and the impact of this on the skills development of both the RWL hosts but also the academic researchers in the project. Doing so can help to bridge the evidence gap on knowledge co-production outcomes [23]. Much of the learning emerges directly from the process in the local/regional context and cannot be predicted or planned for in specific training activities. Creating additional space for shared and critical reflection among practitioners and academic researchers is important for co-designing engagement processes to enable knowledge co-production. To support group reflexivity across the four RWLs, learning exchanges that encourage critical reflection are planned between RWL hosts as part of the training activities, as well as in-person exchange between RWL stakeholders from different regions at consortium meetings.

5. Conclusions

This paper puts forward a structure for knowledge co-production capacities - collaborative capacity, systems-thinking capacity, creative capacity and reflexive capacity - distinguishing between the design, research and facilitation skills needed to develop these capacities. The structure was developed based on literature and real-world experience from the first phase of the DIRECTED project, where a capacity development programme targeted skills development among practitioners (RWL hosts) working on DRM and CCA. These capacities and skills also proved to be relevant for the academic researchers who support practitioners in these processes to develop context-specific technical and governance solutions. The strengths and challenges around supporting practitioners to develop and apply these skills within knowledge co-production processes were shared, for example, some initial reluctance to engage in creative interactive methods. Insights from trainers demonstrated the importance of two-way learning and a capacity development approach that adapts and responds to the practitioners' needs and provides ongoing support and guidance.

Large transdisciplinary projects have huge potential to support emerging transdisciplinarians by building capacity for knowledge production among practitioners and academic researchers to support locally-led processes that develop contextually relevant solutions and influence change in DRM/CCA policy and practice. However, our findings show that this takes time and requires a slow and steady approach dictated by the DRM/CCA practitioners, local context and interest from local stakeholders. The paper highlights the importance of reflecting and measuring the effectiveness of capacity development on the RWL practitioners to influence the knowledge co-production process and outcomes, early and continuously throughout the process. Knowledge co-production not only has value in strengthening practitioners' skills, but two-way learning has wider potential for building skills of academic researchers supporting the process and influencing how models and tools are co-developed. The RWL setup with locally based technical support partners and targeted capacity development approach provides a practical way to enable knowledge co-production that is actionable and context specific, supporting locally-led climate and disaster risk management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105398.

Data availability

Data will be made available on request.

References

[1] WMO, State of the Global Climate 2022, World Meteorological Organisation, 2023. https://library.wmo.int/records/item/66214-state-of-the-global-climate-2022.
[2] H. Visser, A.C. Petersen, W. Ligtvoet, On the relation between weather-related disaster impacts, vulnerability and climate change, Clim. Change 125 (2014) 461–477, https://doi.org/10.1007/s10584-014-1179-z.
[3] UNDRR, CRED, Human cost of disasters. An overview of the last 20 years 2000-2019, Centre for Research on the Epidemiology of Disasters (CRED) and United Nations Office for Disaster Risk Reduction, 2020. https://www.undrr.org/publication/human-cost-disasters-overview-last-20-years-2000-2019.
[4] EEA, European Climate Risk Assessment (Publication), European Environment Agency, 2024. https://www.eea.europa.eu/en/analysis/publications/european-climate-risk-assessment.
[5] A. Anisimov, A.K. Mangan, The Global Transboundary Climate Risk Report, Institute for Sustainable Development and International Relations & Adaptation Without Borders, 2023. https://www.sei.org/publications/transboundary-climate-risk-report-2023/.
[6] A. Boin, The transboundary crisis: why we are unprepared and the road ahead, J. Contingencies Crisis Manag. 27 (2019) 94–99, https://doi.org/10.1111/1468-5973.12241.
[7] J. Sillmann, I. Christensen, S. Hochrainer-Stigler, J. Huang-Lachmann, S. Juhola, K. Kornhuber, M. Mahecha, R. Mechler, M. Reichstein, A.C. Ruane, P.-J. Schweizer, S. Wiliiams, ISC-UNDRR-RISK KAN briefing note on systemic risk. https://doi.org/10.24948/2022.01, 2022.
[8] R. Coyne, Wicked problems revisited, Des. Stud. 26 (2005) 5–17, https://doi.org/10.1016/j.destud.2004.06.005.
[9] B.W. Head, Wicked problems in public policy, Public Policy 3 (2008) 101–118. https://www.academia.edu/57983106/Wicked_Problems_in_Public_Policy.
[10] S. Hochrainer-Stigler, R.Š. Trogrlić, K. Reiter, P.J. Ward, M.C. de Ruiter, M.J. Duncan, S. Torresan, R. Ciurean, J. Mysiak, D. Stuparu, S. Gottardo, Toward a framework for systemic multi-hazard and multi-risk assessment and management, iScience 26 (2023), https://doi.org/10.1016/j.isci.2023.106736.
[11] Z. Stalhandske, C.B. Steinmann, S. Meiler, I.J. Sauer, T. Vogt, D.N. Bresch, C.M. Kropf, Global multi-hazard risk assessment in a changing climate, Sci. Rep. 14 (2024) 5875, https://doi.org/10.1038/s41598-024-55775-2.
[12] E. Daniels, S. Bharwani, Å. Gerger Swartling, G. Vulturius, K. Brandon, Refocusing the climate services lens: introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience, Clim. Serv. 19 (2020) 100181, https://doi.org/10.1016/j.cliser.2020.100181.
[13] C.D. Jack, R. Jones, L. Burgin, J. Daron, Climate risk narratives: an iterative reflective process for co-producing and integrating climate knowledge, Clim. Risk Manag. 29 (2020) 100239, https://doi.org/10.1016/j.crm.2020.100239.
[14] M.C. Lemos, C.J. Kirchhoff, V. Ramprasad, Narrowing the climate information usability gap, Nat. Clim. Change 2 (2012) 789–794, https://doi.org/10.1038/nclimate1614.
[15] J. Weichselgartner, P. Pigeon, The role of knowledge in disaster risk reduction, Int. J. Disaster Risk Sci. 6 (2015) 107–116, https://doi.org/10.1007/s13753-015-0052-7.
[16] K. Schröter, P.-J. Schweizer, B. Gräler, L. Cumiskey, S. Bharwani, J. Parviainen, C. Kropf, V.W. Hakansson, M. Drews, T. Irvine, C. Dondi, H. Apel, J. Löhrlein, S. Hochrainer-Stigler, S. Bagli, L. Huszti, C. Genillard, S. Unguendoli, M. Steinhausen, Invited perspectives: fostering interoperability of data, models, communication and governance for disaster resilience through transdisciplinary knowledge co-production (in review), Nat. Hazards Earth Syst. Sci. Discuss. Prepr. 1–24 (2024), https://doi.org/10.5194/nhess-2024-135.
[17] N. Dias, P. Amaratunga, R. Haigh, G. Clegg, C. Malalgoda, in: Critical Factors that Hinder Integration of CCA and DRR: Global Perspective, 2021, pp. 1–22, https://doi.org/10.1007/978-3-030-22759-3_124-1.
[18] T. Izumi, R. Shaw, R. Djalante, M. Ishiwatari, T. Komino, Disaster risk reduction and innovations, Prog. Disaster Sci. 2 (2019) 100033, https://doi.org/10.1016/j.pdisas.2019.100033.
[19] A. Bendito, E. Barrios, Convergent agency: encouraging transdisciplinary approaches for effective climate change adaptation and disaster risk reduction, Int. J. Disaster Risk Sci. 7 (2016) 430–435, https://doi.org/10.1007/s13753-016-0102-9.
[20] M.G. Lawrence, S. Williams, P. Nanz, O. Renn, Characteristics, potentials, and challenges of transdisciplinary research, One Earth 5 (2022) 44–61, https://doi.org/10.1016/j.oneear.2021.12.010.
[21] S. Bharwani, Å. Gerger Swartling, K. André, T.F. Santos Santos, A. Salamanca, N. Biskupska, T. Takama, L. Järnberg, A. Liu, Co-designing in tandem: case study journeys to inspire and guide climate services, Clim. Serv. 35 (2024) 100503, https://doi.org/10.1016/j.cliser.2024.100503.
[22] A.V. Norström, C. Cvitanovic, M.F. Löf, S. West, C. Wyborn, P. Balvanera, A.T. Bednarek, E.M. Bennett, R. Biggs, A. de Bremond, B.M. Campbell, J.G. Canadell, S.R. Carpenter, C. Folke, E.A. Fulton, O. Gaffney, S. Gelcich, J.-B. Jouffray, M. Leach, M. Le Tissier, B. Martín-López, E. Louder, M.-F. Loutre, A.M. Meadow, H. Nagendra, D. Payne, G.D. Peterson, B. Reyers, R. Scholes, C.I. Speranza, M. Spierenburg, M. Stafford-Smith, M. Tengö, S. van der Hel, I. van Putten, H. Österblom, Principles for knowledge co-production in sustainability research, Nat. Sustain. 3 (2020) 182–190, https://doi.org/10.1038/s41893-019-0448-2.
[23] K. Jagannathan, J.C. Arnott, C. Wyborn, N. Klenk, K.J. Mach, R.H. Moss, K.D. Sjostrom, Great expectations? Reconciling the aspiration, outcome, and possibility of co-production, Curr. Opin. Environ. Sustain., Adv. Sci. Actionable Knowl. Sustain. 42 (2020) 22–29, https://doi.org/10.1016/j.cosust.2019.11.010.
[24] M.K. van Aalst, T. Cannon, I. Burton, Community level adaptation to climate change: the potential role of participatory community risk assessment. Glob, Environ. Change 18 (2008) 165–179, https://doi.org/10.1016/j.gloenvcha.2007.06.002.

[25] M. Hagelsteen, P. Becker, Systemic problems of capacity development for disaster risk reduction in a complex, uncertain, dynamic, and ambiguous world, Int. J. Disaster Risk Reduct. 36 (2019) 101102, https://doi.org/10.1016/j.ijdrr.2019.101102.
[26] Å. Johannessen, Å. Gerger Swartling, C. Wamsler, K. Andersson, J.T. Arran, D.I. Hernández Vivas, T.A. Stenström, Transforming urban water governance through social (triple-loop) learning, Environ. Policy Gov. 29 (2019) 144–154, https://doi.org/10.1002/eet.1843.
[27] A. Haas, Crowding at the frontier: boundary spanners, gatekeepers and knowledge brokers, J. Knowl. Manag. 19 (2015) 1029–1047, https://doi.org/10.1108/JKM-01-2015-0036.
[28] P. Williams, The life and times of the boundary spanner, J. Integrated Care 19 (2011) 26–33, https://doi.org/10.1108/14769011111148140.
[29] P.D. Gluckman, A. Bardsley, M. Kaiser, Brokerage at the science–policy interface: from conceptual framework to practical guidance, Humanit. Soc. Sci. Commun. 8 (2021) 1–10, https://doi.org/10.1057/s41599-021-00756-3.
[30] A. Hammill, B. Harvey, D. Echeverría, Knowledge for action: an analysis of the use of online climate knowledge brokering platforms, Knowl. Manag. Dev. J. 9 (2013) 72–92. https://km4djournal.org/index.php/km4dj/article/view/136.
[31] S. Meijerink, D. Huitema, Policy entrepreneurs and change strategies: lessons from sixteen case studies of water transitions around the globe, Ecol. Soc. 15 (2010), https://doi.org/10.5751/ES-03509-150221.
[32] B. Cosens, J.B. Ruhl, N. Soininen, L. Gunderson, A. Belinskij, T. Blenckner, A.E. Camacho, B.C. Chaffin, R.K. Craig, H. Doremus, R. Glicksman, A.-S. Heiskanen, R. Larson, J. Similä, Governing complexity: integrating science, governance, and law to manage accelerating change in the globalized commons, Proc. Natl. Acad. Sci. 118 (2021) e2102798, https://doi.org/10.1073/pnas.2102798118.
[33] D. Stokols, Training the next generation of transdisciplinarians, in: Enhancing Communication & Collaboration in Interdisciplinary Research, SAGE Publications, Inc., United States, 2014, pp. 56–81, https://doi.org/10.4135/9781483352947.n4.
[34] S. Hoffmann, L. Deutsch, J.T. Klein, M. O'Rourke, Integrate the integrators! A call for establishing academic careers for integration experts, Humanit. Soc. Sci. Commun. 9 (2022) 1–10, https://doi.org/10.1057/s41599-022-01138-z.
[35] D. McCullagh, G.S. Langendijk, G. Winter, A. Jeuken, L. Cumiskey, P. Medway, D. Carr, R. Gingles, D. Dunne, W. Camaro, Climate services: co-development in Cork City, Ireland, Soc. Impacts 4 (2024) 100072, https://doi.org/10.1016/j.socimp.2024.100072.
[36] S.E. Kalafatis, M.C. Lemos, Y.-J. Lo, K.A. Frank, Increasing information usability for climate adaptation: the role of knowledge networks and communities of practice, Glob. Environ. Change 32 (2015) 30–39, https://doi.org/10.1016/j.gloenvcha.2015.02.007.
[37] M. Bergmann, N. Schäpke, O. Marg, F. Stelzer, D.J. Lang, M. Bossert, M. Gantert, E. Häußler, E. Marquardt, F.M. Piontek, T. Potthast, R. Rhodius, M. Rudolph, M. Ruddat, A. Seebacher, N. Sußmann, Transdisciplinary sustainability research in real-world labs: success factors and methods for change, Sustain. Sci. 16 (2021) 541–564, https://doi.org/10.1007/s11625-020-00886-8.
[38] M. Hildén, A. Jordan, D. Huitema, Special issue on experimentation for climate change solutions editorial: the search for climate change and sustainability solutions - the promise and the pitfalls of experimentation, J. Clean. Prod., Exp. Clim. Change Solut. 169 (2017) 1–7, https://doi.org/10.1016/j.jclepro.2017.09.019.
[39] M. Leitner, D. Buschmann, T.C. Lourenço, I. Coninx, A. Schmidt, Bonding CCA and DRR: recommendations for strengthening institutional coordination and capacities. https://research.wur.nl/en/publications/bonding-cca-and-drr-recommendations-for-strengthening-institution, 2020.
[40] G. Ziervogel, J. Enqvist, L. Metelerkamp, J. van Breda, Supporting transformative climate adaptation: community-level capacity building and knowledge co-creation in South Africa, Clim. Policy 22 (2022) 607–622, https://doi.org/10.1080/14693062.2020.186318.
[41] J. Parviainen, S. Bharwani, L. Cumiskey, P. Mazzoli, P.-J. Schweizer, T. Irvine, R. Witton, M. Drews, E. Ronde Nielsen, A. Laursen, J. Lohrlein, J. Struck, V. Pancioli, D. Hedderich, G. Ben, DIRECTED deliverable 1.2 capacity development strategy for DIRECTED: Training of Trainers – Implementing transdisciplinary knowledge co-production processes in Real World Labs, 2024.
[42] M. Hossain, S. Leminen, M. Westerlund, A systematic review of living lab literature, J. Clean. Prod. 213 (2019) 976–988, https://doi.org/10.1016/j.jclepro.2018.12.257.
[43] G. McCrory, N. Schäpke, J. Holmén, J. Holmberg, Sustainability-oriented labs in real-world contexts: an exploratory review, J. Clean. Prod. 277 (2020) 123202, https://doi.org/10.1016/j.jclepro.2020.123202.
[44] R. Sieber, L. Faulenbach, M. Fuchs, L. Gülleken, The challenges of co-research in labs in real-world contexts: empirical findings from four labs in the context of urban climate-change research, Town Plan. Rev. 93 (2022) 139–163, https://doi.org/10.3828/tpr.2021.24.
[45] J. Parviainen, S. Hochrainer-Stigler, L. Cumiskey, S. Bharwani, P.-J. Schweizer, B. Hofbauer, D. Cubie, The risk-tandem framework: an iterative framework for combining risk governance and knowledge co-production toward integrated disaster risk management and climate change adaptation, Int. J. Disaster Risk Reduct. 116 (2025) 105070, https://doi.org/10.1016/j.ijdrr.2024.105070.
[46] J.R.A. Butler, R.M. Wise, T.D. Skewes, E.L. Bohensky, N. Peterson, W. Suadnya, Y. Yanuartati, T. Handayani, P. Habibi, K. Puspadi, N. Bou, D. Vaghelo, W. Rochester, Integrating top-down and Bottom-Up adaptation planning to build adaptive capacity: a structured learning approach, Coast. Manag. 43 (2015) 346–364, https://doi.org/10.1080/08920753.2015.1046802.
[47] A. McClure, J. Daron, S. Bharwani, R. Jones, L.C. Grobusch, J. Kavonic, T. Janes, M. Zhang, E. Hill, M. Mzime, Principles for co-producing climate services: practical insights from FRACTAL, Clim. Serv. 34 (2024) 100492, https://doi.org/10.1016/j.cliser.2024.100492.
[48] R. Spiekermann, S. Kienberger, J. Norton, F. Briones, J. Weichselgartner, The disaster-knowledge matrix – reframing and evaluating the knowledge challenges in disaster risk reduction, Int. J. Disaster Risk Reduct. 13 (2015) 96–108, https://doi.org/10.1016/j.ijdrr.2015.05.002.
[49] P. Tosey, M. Visser, M.N. Saunders, The origins and conceptualizations of 'triple-loop' learning: a critical review, Manag. Learn. 43 (2011), https://doi.org/10.1177/1350507611426239.
[50] J. Sharpe, Understanding and unlocking transformative learning as a method for enabling behaviour change for adaptation and resilience to disaster threats, Int. J. Disaster Risk Reduct. 17 (2016) 213–219, https://doi.org/10.1016/j.ijdrr.2016.04.014.
[51] F. van der Molen, How knowledge enables governance: the coproduction of environmental governance capacity, Environ. Sci. Pol. 87 (2018) 18–25, https://doi.org/10.1016/j.envsci.2018.05.016.
[52] C.A. Miller, C. Wyborn, Co-production in global sustainability: Histories and theories, Environ. Sci. Policy 113 (2020) 88–95, https://doi.org/10.1016/j.envsci.2018.01.016. Into the fray. Strategic perspectives on biodiversity sciences and politics.
[53] B. Glaser, A. Strauss, The Discovery of Grounded Theory, Routledge, 1967.
[54] L. Vaughan, Practice-Based Design Research, Bloomsbury Publishing, 2017. https://books.google.ie/books?id=H8XIDQAAQBAJ&lpg=PP1&dq=%5B54%5D%20L.%20Vaughan%2C%20Practice-based%20Design%20Research%2C%20Bloomsbury%20Publishing%2C%202017&lr&pg=PP1#v=onepage&q=%5B54%5D%20L.%20Vaughan,%20Practice-based%20Design%20Research,%20Bloomsbury%20Publishing,%202017&f=false.
[55] K. Vincent, A. Steynor, A. McClure, E. Visman, K.L. Waagsaether, S. Carter, N. Mittal, Co-production: learning from contexts, in: D. Conway, K. Vincent (Eds.), Climate Risk in Africa: Adaptation and Resilience, Springer International Publishing, Cham, 2021, pp. 37–56, https://doi.org/10.1007/978-3-030-61160-6_3.
[56] K. Vincent, S. Carter, A. Steynor, E. Visman, K.L. Wågsæther, Addressing power imbalances in co-production, Nat. Clim. Change 10 (2020) 877–878, https://doi.org/10.1038/s41558-020-00910-w.
[57] K. Hölscher, N. Frantzeskaki, D. Kindlon, M.J. Collier, G. Dick, A. Dziubała, M. Lodder, A. Osipiuk, M. Quartier, S. Schepers, K.V. De Sijpe, C. van der Have, Embedding co-production of nature-based solutions in urban governance: emerging co-production capacities in three European cities, Environ. Sci. Pol. 152 (2024) 103652, https://doi.org/10.1016/j.envsci.2023.103652.
[58] A. McCabe, R. Parker, T. Osegowitsch, S. Cox, Overcoming barriers to knowledge co-production in academic–practitioner research collaboration, Eur. Manag. J. 41 (2023) 212–222, https://doi.org/10.1016/j.emj.2021.11.009.
[59] A. Rosemartin, T.M. Crimmins, K.L. Gerst, E.E. Posthumus, A.R. Ramirez, C.S. Wallace, T.L. Morelli, Lessons learned in knowledge co-production for climate-smart decision-making, Environ. Sci. Pol. 141 (2023) 178–187, https://doi.org/10.1016/j.envsci.2023.01.010.
[60] C.D. Jack, J. Marsham, D.P. Rowell, R.G. Jones, Climate information: towards transparent distillation, in: D. Conway, K. Vincent (Eds.), Climate Risk in Africa: Adaptation and Resilience, Springer International Publishing, Cham, 2021, pp. 17–35, https://doi.org/10.1007/978-3-030-61160-6_2.

[61] S. Bremer, A. Wardekker, S. Dessai, S. Sobolowski, R. Slaattelid, J. van der Sluijs, Toward a multi-faceted conception of co-production of climate services, Clim. Serv. 13 (2019) 42–50, https://doi.org/10.1016/j.cliser.2019.01.003.
[62] T.U. Wall, A.M. Meadow, A. Horganic, Developing evaluation indicators to improve the process of coproducing useable climate science. https://doi.org/10.1175/WCAS-D-16-0008.1, 2017.
[63] J.D. Daron, S. Lorenz, P. Wolski, R.C. Blamey, C. Jack, Interpreting climate data visualisations to inform adaptation decisions, Clim. Risk Manag. 10 (2015) 17–26, https://doi.org/10.1016/j.crm.2015.06.007.
[64] D.A. Stainforth, M.R. Allen, E.R. Tredger, L.A. Smith, Confidence, uncertainty and decision-support relevance in climate predictions, Philos. Trans. R. Soc. Math. Phys. Eng. Sci. 365 (2007) 2145–2161, https://doi.org/10.1098/rsta.2007.2074.
[65] D.H. Meadows, Leverage points toward a sustainable world, in: Global Environmental Politics, Routledge, 2015. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315479057-39/leverage-points-toward-sustainable-world-donella-meadows.
[66] A. Wiek, L. Withycombe, C.L. Redman, Key competencies in sustainability: a reference framework for academic program development, Sustain. Sci. 6 (2011) 203–218, https://doi.org/10.1007/s11625-011-0132-6.
[67] S. Hochrainer-Stigler, T.M. Deubelli-Hwang, J. Parviainen, L. Cumiskey, P.-J. Schweizer, U. Dieckmann, Managing systemic risk through transformative change: combining systemic risk analysis with knowledge co-production, One Earth 7 (2024) 771–781, https://doi.org/10.1016/j.oneear.2024.04.014.
[68] T.G. Shepherd, E. Boyd, R.A. Calel, S.C. Chapman, S. Dessai, I.M. Dima-West, H.J. Fowler, R. James, D. Maraun, O. Martius, C.A. Senior, A.H. Sobel, D. A. Stainforth, S.F.B. Tett, K.E. Trenberth, B.J.J.M. van den Hurk, N.W. Watkins, R.L. Wilby, D.A. Zenghelis, Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Clim. Change 151 (2018) 555–571, https://doi.org/10.1007/s10584-018-2317-9.
[69] M.C. de Ruiter, A. Couasnon, P.J. Ward, Breaking the silos: an online serious game for multi-risk disaster risk reduction (DRR) management, Geosci. Commun. 4 (2021) 383–397, https://doi.org/10.5194/gc-4-383-2021.
[70] T.-S. Neset, L. Andersson, O. Uhrqvist, C. Navarra, Serious gaming for climate adaptation—assessing the potential and challenges of a digital serious game for urban climate adaptation, Sustainability 12 (2020) 1789, https://doi.org/10.3390/su12051789.
[71] N. Li, N. Sun, C. Cao, S. Hou, Y. Gong, Review on visualization technology in simulation training system for major natural disasters, Nat. Hazards 112 (2022) 1851–1882, https://doi.org/10.1007/s11069-022-05277-z.
[72] K. Vincent, M. Daly, C. Scannell, B. Leathes, What can climate services learn from theory and practice of co-production? Clim. Serv. 12 (2018) 48–58, https://doi.org/10.1016/j.cliser.2018.11.001.
[73] B. Lam, T. Zamenopoulos, M. Kelemen, J. Hoo Na, Unearth hidden assets through community Co-design and Co-production, Des. J. 20 (2017) S3601–S3610, https://doi.org/10.1080/14606925.2017.1352863.
[74] C. Mainemelis, S. Ronson, Ideas are born in fields of play: towards a theory of play and creativity in organizational settings, Res. Organ. Behav. 27 (2006) 81–131, https://doi.org/10.1016/S0191-3085(06)27003-5.
[75] S. Mackay, E. Ellison, W. Bennett, Natural disaster resilience and the creative arts: a case study from rural Australia, J. Arts Commun. 15 (2024) 57–73, https://doi.org/10.1386/jaac_00054_1.
[76] J. Ristić Trajković, J. Bentz, Creative Methods Toolkit for Imagining, Designing and Teaching Regenerative Futures, NOVA University of Lisbon – FCSH, Lisbon, 2024. https://shift-cost.eu/wp-content/uploads/2024/11/Final-Toolkit_compressed.pdf.
[77] A.F. Van Loon, I. Lester-Moseley, M. Rohse, P. Jones, R. Day, Creative practice as a tool to build resilience to natural hazards in the Global South, Geosci. Commun. 3 (2020) 453–474, https://doi.org/10.5194/gc-3-453-2020.
[78] K. Yusoff, J. Gabrys, Climate change and the imagination, WIREs Clim. Change 2 (2011) 516–534, https://doi.org/10.1002/wcc.117.
[79] The Wellcome Trust, Creative policy dialogues through serious fun – humour and acrobatics to confront climate and mental health [version 1; not peer reviewed], Wellcome Open Res. 173 (1) (2024), https://doi.org/10.21955/wellcomeopenres.1115381.
[80] L. Le Dé, J. Gaillard, A. Gampell, N. Loodin, G. Hinchliffe, Fostering children's participation in disaster risk reduction through play: a case study of LEGO and minecraft, Int. J. Disaster Risk Sci. 12 (2021) 867–878, https://doi.org/10.1007/s13753-021-00375-1.
[81] O.S. Iversen, K. Halskov, T.W. Leong, Values-led participatory design, CoDesign 8 (2012) 87–103, https://doi.org/10.1080/15710882.2012.672575.
[82] N. Schäpke, F. Stelzer, G. Caniglia, M. Bergmann, M. Wanner, M. Singer-Brodowski, D. Loorbach, P. Olsson, C. Baedeker, D.J. Lang, Jointly experimenting for transformation? Shaping real-world laboratories by comparing them, GAIA - Ecol. Perspect. Sci. Soc. 27 (2018) 85–96, https://doi.org/10.14512/gaia.27.S1.16.
[83] M. Polk, Transdisciplinary co-production: designing and testing a transdisciplinary research framework for societal problem solving, Futures 65 (2015) 110–122, https://doi.org/10.1016/j.futures.2014.11.001. Advances in transdisciplinarity 2004-2014.
[84] J. Godemann, Knowledge integration: a key challenge for transdisciplinary cooperation, Environ. Educ. Res. 14 (2008) 625–641, https://doi.org/10.1080/13504620802469188.
[85] J. Mezirow, Transformative learning: theory to practice, N. Dir. Adult Cont. Educ. (1997) 5–12, https://doi.org/10.1002/ace.7401, 1997.
[86] D.M. Vollmer, F. Mulder, S. Kundsen, V. Hollmann, Fostering Collaboration to Close the Risk Perception-Action Gap. RiskPACC White Paper and Roadmap, RiskPACC, 2024, https://doi.org/10.13140/RG.2.2.33027.11045.
[87] P.-J. Schweizer, R. Goble, O. Renn, Social perception of systemic risks, Risk Anal. 42 (2022) 1455–1471, https://doi.org/10.1111/risa.13831.
[88] C. Cvitanovic, J. McDonald, A.J. Hobday, From science to action: principles for undertaking environmental research that enables knowledge exchange and evidence-based decision-making, J. Environ. Manag. 183 (2016) 864–874, https://doi.org/10.1016/j.jenvman.2016.09.038.
[89] I. Gram-Hanssen, C. Aall, M. Drews, S. Juhola, A. Jurgilevich, R.J.T. Klein, M.A. Mikaelsson, V. Lyngtorp Mik-Meyer, Towards Enhanced Climate Change Adaptation in the Nordic Region: Policy Recommendations Based on an Assessment of Best Practices and Key Challenges for Adaptation Policy in the Nordic Countries, Nordic Council of Ministers, 2023, https://doi.org/10.6027/nord2023-014.
[90] S.L.T. McGregor, Understanding and Evaluating Research: a Critical Guide, SAGE Publications, 2018. https://methods.sagepub.com/book/mono/understanding-and-evaluating-research/toc.