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Transdisciplinary Knowledge Production for Integrated Climate Risk Management: Application of a Framework in the Dutch Urbanized Delta

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ABSTRACT

Climate change increasingly impacts the built environment through rising sea levels, intensifying heatwaves, and frequent extreme weather events, especially in low-lying, densely populated countries like the Netherlands. Despite growing urgency, current climate risk management strategies are rather individuated by firms, and siloed across sectors. A lack of shared, accessible knowledge on climate risks to real estate and infrastructure hinders coordinated, transparent, and integrated decision-making. This highlights the need for structured transdisciplinary approaches that foster collaboration between researchers and practitioners to co-produce knowledge and develop integrated adaptation solutions.

This article introduces a novel framework to facilitate transdisciplinary knowledge production for integrated real estate and infrastructure climate risk management. Using a mixed-method approach, the framework is developed through a literature review on transdisciplinary research and further evolved by incorporating practice-based empirical insights and collective experiential learning gained during its application within the Red&Blue (Real Estate Development and Building in Low Urban Environments) case study.

The framework comprises four interconnected phases: (1) knowledge elicitation through a three-layer stakeholder engagement and impact plan, (2) knowledge exploration by combining the institutionalized logics theory and AI-supported techniques, (3) knowledge integration, and (4) knowledge transformation.

Applying the framework to the Red&Blue case study reveals that effective transdisciplinary knowledge production requires not only a structured process but also an adaptive, and iterative approach. Key enablers include sustained stakeholders engagement, safe-space dialogue, conscious knowledge integration, and integrative leadership. These elements foster trust, improve communication, and support the co-creation of actionable and transferable knowledge to address complex climate risk and sustainability challenges in urbanized built environments in the Netherlands and beyond.

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1. Introduction

Climate change causes substantial adverse impacts on real estate and infrastructure systems in various ways. Physical impacts of climate change such as sea level rise, heat waves, and frequent and intense storms cause broad socio-economic-environmental damages. These interlinked impacts threaten homes and other real estate assets, infrastructure systems and their vital services, financial and societal stability, and the institutional capacity to deal with these impacts. Such impacts are exacerbated in low lying and densely populated deltas such as the western part of the Netherlands where the quality and value of the built environment are increasingly under climate-driven pressures. According to Delta Program Commissioner (2020), damages to the Dutch infrastructure and real estate are estimated to be from €33 to €124 billion by the year 2050. In particular, Amsterdam and Rotterdam are the cities which are growingly exposed to the effects of climate change, and this calls for spatial investments and innovative approaches from government, firms, and citizens alike.

The country is internationally recognized for its advanced climate adaptation frameworks and institutionalized water and flood risk management. Examples include KNMI'23 climate scenarios (KNMI, 2023), the Klimaateffectatlas, providing detailed flood, heat, and drought risk maps, mandatory municipal stress tests since 2014 under the Delta Programme, multi-layer safety (MLS) approach (Rijke et al., 2012; van Buuren et al., 2016), and the Framework for Climate Adaptive Buildings (DGBC, 2021).

Despite these advances, challenges remain in achieving cross-sectoral integration of climate risk knowledge. Fragmentation and siloed approaches continue to limit integration between water management, spatial planning, and financial decision-making (van Buuren and Teisman, 2014; Uittenbroek et al., 2019). Dutch scholarship on policy integration and adaptation governance highlights these persistent barriers—despite strong institutional capacities—pointing to entrenched sectoral logics and path dependencies that complicate cross-sector alignment (Dewulf et al., 2015; Mees et al., 2018; Termeer et al., 2017). Similarly, an advisory report by Rli (Raad voor de leefomgeving en infrastructuur) examining spatial planning in a changing climate highlights persistent governance and coordination challenges across sectors, pointing to variations in methods and institutional capacities (Rli, 2024). Spatial planning and financial sectors continue to interpret and apply climate risk information differently. For instance, a study by DNB (2017) shows that many insurers and financial institutions in the Netherlands still rely on catastrophe models that do not explicitly account for national climate change trends, revealing a gap in translating physical climate risk into asset valuation and risk modelling.

There is also a knowledge gap concerning the interplay between urban-scale climate risk management and delta system-level action, as the MLS approach evolves under changing conditions—raising questions about strategies, institutional responsibilities, and interdependencies (Dewulf and Klenk, 2021). At the same time, regulators and adaptation agencies increasingly call for engaging the financial sector in the co-production of delta-related knowledge. The launch of the "NLAAA Climate Proof" initiative of the National Delta Program (Delta Program Commissioner, 2023), which expressly connects the financial sector with the Dutch delta management community indicates recognition of this urgency to extend existing expertise in engineering-centric delta management strategies to new stakeholders, spatial scales, and integrated approaches.

The above-mentioned gaps support the contention that even in the advanced Dutch climate adaptation context, interpretation and operationalisation of climate risk management remain uneven across sectors. Strengthening the transdisciplinary production of shared and actionable climate knowledge is therefore essential to connect technical, legal, financial, and social dimensions of risk, and to support long-term resilience of the Dutch built environment and beyond. However, the key question is: *what kind of process can produce shared, actionable, and embedded knowledge across silos?*

The concept of knowledge production in transdisciplinary research and practice has been frequently explored in literature. Some studies (i.e., Bammer, 2013; Buser and Schneider, 2021; Scholz et al, 2024) related it to the types of knowledge integration, and different definitions and interpretations of it (e.g., Okhuysen and Eisenhardt, 2002; Berggren et al., 2011; Mehrabani and Shajari, 2012; Martini et al., 2017; Gong et al., 2022; Li et al., 2023), while others explored it within a case study in a particular context such as health and well-being (Wardani et al., 2023; Dennis et al., 2023); agriculture (Salite and Poskitt, 2019; Jellason et al., 2022); disaster risk reduction (Hermans et al., 2022); sustainability (Ramakrishna et al., 2023); and urban resilience (Gaete Cruz, 2023). In some literature (e.g., Stal et al., 2014; Osei-Amponsah et al., 2018; Franco-Torres et al., 2020; Slacik et al., 2022), knowledge production is experimented by using participatory approaches to draw out and integrate stakeholders' insights and their rationales, perspectives, and (re)actions when dealing with a particular societal challenge, a concept as referred to as "institutional(ized) logics'' (see Thornton and Ocasio, 2008; Thornton et al., 2012; WU et al., 2023).

Despite an increasing acknowledgment of the existing literature on the importance of transdisciplinary knowledge production through integration of perspectives (e.g., Tengö et al., 2014; Guodaar et al., 2021; Jellason et al., 2022; Kang, 2022; Taylor et al., 2023), its implementation in empirical research remains limited yet. Many transdisciplinary efforts tend to focus on surface-level engagement, prioritizing dialogue and interaction over actionable outcomes. Merely providing opportunities for stakeholders to interact does not guarantee meaningful integration. Hoffmann et al. (2022) emphasize the essential role of leadership in transdisciplinary research, drawing attention to a gap in traditional, mono-disciplinary academic roles, which often lack the expertise needed for effective integration. This underscores the importance of structured approaches that deliberately foster both individual and collective capacity to integrate knowledge and promote transdisciplinary collaboration (Mehvar et al., 2025). Specifically, there is limited understanding of how to effectively integrate transdisciplinary knowledge to address the complex challenges of real estate and infrastructure climate risk management. The key question remains: *how can we elicit and incorporate diverse stakeholder perspectives into an integrated, actionable approach that ensures inclusive and transparent decision-making*? This gap highlights the need for a clear, practical, and process-oriented methodology.

This article introduces a novel framework presenting a step-by-step methodology for transdisciplinary Knowledge Production for

integrated Climate Risk Management (KPCRM). The KPCRM framework was developed and evolved using a mixed-method approach that combines a literature review on transdisciplinary research with empirical insights and experiential learning from its application in Red&Blue—a five-year transdisciplinary research and impact program focused on developing, testing, and promoting integrated climate risk management strategies for real estate and infrastructure in the urbanized delta of the Netherlands. The article presents findings from the framework's application, identifying key challenges and enablers in transdisciplinary knowledge production for advancing integrated climate adaptation efforts in the Netherlands and beyond.

The framework consists of four interlinked phases (see Fig. 1); *Knowledge elicitation* facilitates exchanges between scientists and practitioners to surface and align diverse insights. *Knowledge exploration* analyses and reframes the insights—combining institutionalized logics theory and AI-supported techniques—to reveal overlaps, divergences, and synergies. *Knowledge integration* synthesizes and validates findings through iterative reflection and feedback. Finally, *knowledge transformation* translates the integrated insights back into stakeholders' domains, clarifying feasible actions, responsibilities, and implications for practice.

This article is structured as follows: *Section 2* outlines the methodology by presenting the framework's phased approach, drawing on insights from the literature review (as thoroughly reflected in Appendix), and our observations and experiences gained during framework's application to the case study. *Section 3* presents the application results, identifying key transdisciplinary challenges, and proposing enablers for effective knowledge production. *Section 4* discusses key findings, and *Section 5* presents conclusions of the study.

2. Method

To design the KPCRM framework, we employed a mixed-method approach, combining insights derived from a literature review on transdisciplinary knowledge integration (as fully presented in the Appendix) informed by practice-based empirical insights and experiential learning gained through the Red&Blue case study. As the empirical insights were derived from real-world stakeholder engagements rather than triangulated datasets, the framework was evolved iteratively and in direct response to practice. This builds on the preliminary empirical findings described by Mehvar et al. (2025), which outline the Red&Blue integrated approach and draw on practice-based insights from stakeholder interactions, co-creation process, and integrative forum discussions. Overall, this methodological design aligns with the transdisciplinary ideal of combining generalizable approaches with context-specific learning.

Because the Red&Blue knowledge production process is inherently learning-by-doing, its epistemology also combines scientific reasoning with design practice. Not all transdisciplinary insights can be linearly traced to a single data point, instead, understanding

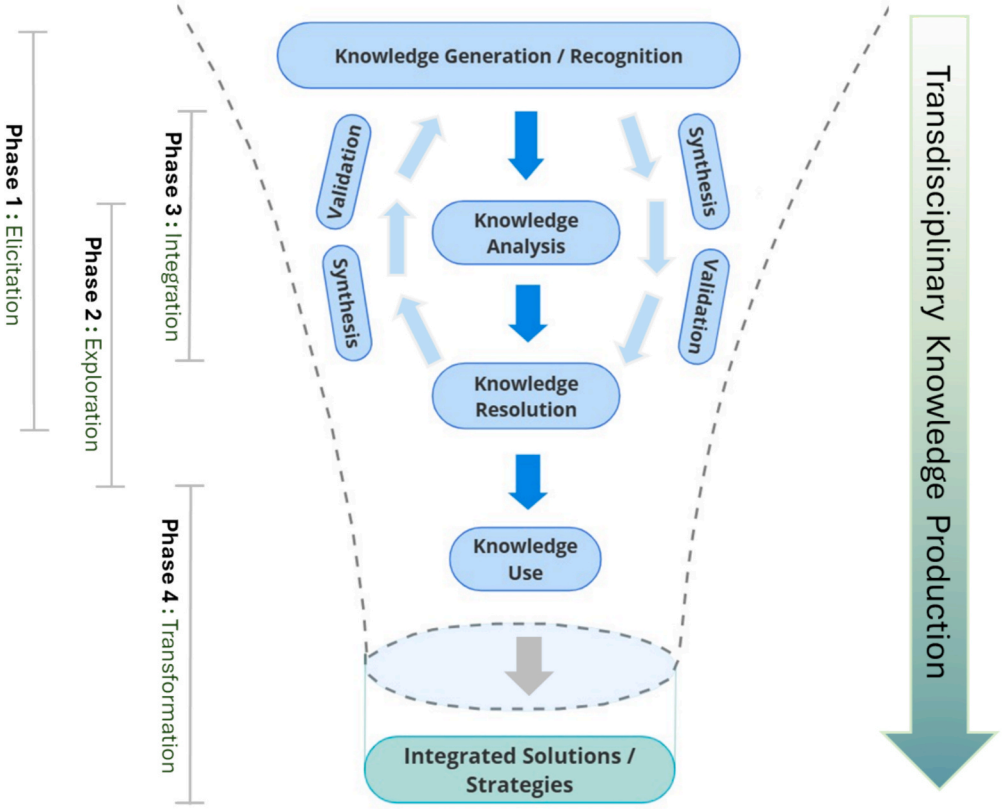

Fig. 1. The KPCRM framework developed in this study, to facilitate transdisciplinary knowledge production through its four-phase approach: knowledge elicitation, exploration, integration, and transformation.

emerges through iterative cycles of reflection, prototyping, and adaptation – an approach resonant with Nigel Cross's concept of *"designerly ways of knowing"* (Cross 2001, 2006). Within this paradigm, experiential and tacit practitioner knowledge are recognised as legitimate epistemic inputs alongside analytical data. The mixed-method approach therefore integrates design-based methods—such as experiential observation, reflective iteration, and co-creative sense-making—into conventional scientific procedures. This integration is an intentional feature of transdisciplinary research, whose aim is to co-produce actionable understanding across disciplinary and institutional boundaries.

For conducting the literature review, the Scopus database was used to identify studies exploring transdisciplinary knowledge integration methods in the context of climate change, thus a search criteria was limited to the keywords "knowledge integration" AND "climate", covering articles and reviews published between 2013 and 2024, yielding 87 studies. Due to the limited results when combining these keywords with "real estate" OR "infrastructure", a separate search for "climate risk" AND "real estate" was conducted, adding 21 publications to our database. Insights from the literature review informed our understanding of transdisciplinary knowledge production and the specific challenges of climate risk management in the Dutch real estate and infrastructure sector. These insights provided the foundation for developing the framework as a generalizable, phase-based methodological tool to facilitate transdisciplinary knowledge co-production within our case study and potentially in other contexts.

The empirical insights were particularly gained through the Red&Blue co-creation process, initiated in 2020 which brought together over fifty Dutch stakeholders from science, policy, and practice in the fields of real estate finance, area development, climate risk assessment, infrastructure design, spatial planning, law, and governance to address knowledge gaps in climate adaptation for urbanized delta areas. Through presentations, discussions, and bilateral meetings, participants recognized the need for a shared vocabulary to analyse real estate and infrastructure climate risk challenges, leading to the identification of seven focal points spanning risk assessment, governance, capacity building, and so on. These exchanges helped to shape the case study's direction and facilitated the establishment of the consortium. This means that the Red&Blue knowledge agenda was co-developed across disciplines, sectors and work packages through joint problem framing (Lang et al., 2012), creating a bridge between interdisciplinary and transdisciplinary collaboration that anchors the framework in collective inquiry.

Since the program's launch in 2022, these exchanges have evolved through the establishment of an integrative forum—a "safe space" enabling transdisciplinary dialogue, collaborative learning, and joint development of climate-informed decision-making capacities. We compiled cross-disciplinary insights through collection of documented notes and summaries from more than 50 bilateral discussions, workshops, expert meetings, symposiums, and knowledge exchange sessions during the co-creation process and development of the integrative forum.

Building on both literature and empirically informed practice-based insights, we developed the KPCRM framework including a four-phase process as described below:

2.1. Phase 1 — Knowledge Elicitation

The co-creation process led us to design a three-layer stakeholder engagement and impact plan (see Fig. 2). This plan serves as a foundation for facilitating dialogue and recognizing diverse forms of inter- and transdisciplinary knowledge exchanges, forming the *knowledge elicitation* phase.

This structured approach ensures that discussions, debates, and insights are effectively shared across different groups, enhancing both internal and external engagement. At the core of this plan is Layer 1, which focuses on internal consortium collaboration. Within this layer, researchers actively participate in scientific workshops and monthly lab meetings. Additionally, they engage in urban use case interactions with practitioners, fostering a deeper connection between academic insights and real-world applications. In addition, the entire consortium comes together annually for the annual forum or symposium, providing a platform to reflect on progress, share findings and identify future directions.

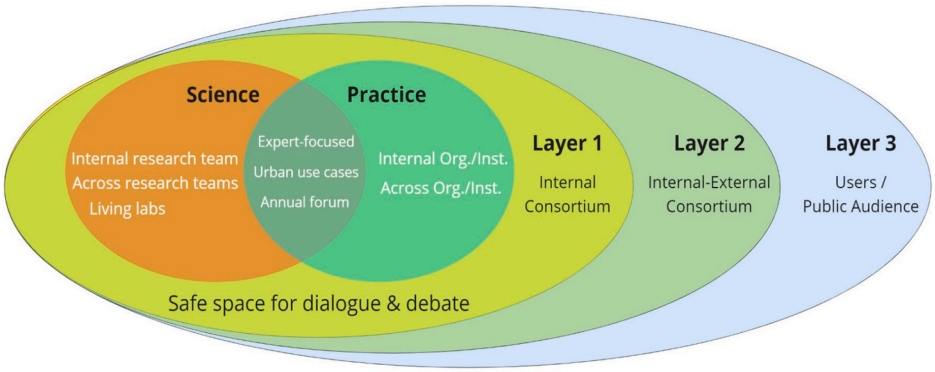

Fig. 2. Knowledge elicitation through the facilitation of diverse exchange activities between researchers and practitioners, structured according to the Red&Blue three-layer engagement and impact plan (adapted from Mehvar et al., 2025). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Expanding beyond the consortium, Layer 2 bridges internal and external experts, facilitating targeted interactions that connect consortium members with key stakeholders outside the immediate research network. These interactions create opportunities for cross-sector collaboration, ensuring that expertise and perspectives from various disciplines contribute to the broader conversation on climate risk management. Finally, Layer 3 broadens the reach even further by engaging end-users and the public audience, fostering knowledge-sharing beyond academic and professional circles. Some examples of these knowledge exchanges during the past 2.5 years of the program are reported by Mehvar (2023a, 2023b, 2024).

To systematically elicit and document the knowledge shared through these interactions, a primary source of data has been developed. This includes anonymized meeting notes, and summaries of discussions from the integrative forum. It captures knowledge exchanges at multiple levels, including interactions among research teams, practitioners, and cross-sector collaborations focused on specific climate risk challenges and potential adaptation solutions in urban use cases. To enhance data reliability and ensure a comprehensive record of transdisciplinary insights, selected expert-focused meetings and debates were recorded and transcribed using AI-supported tools. For doing this, we considered three different approaches to recording data from the meetings with an informed consent from participants:

1. Use of a central microphone to record the discussions.
2. A setup in which each participant is equipped with an individual microphone.
3. Use of the 'Shape Language' method (Caldari et al., 2019) for which participants are organized into smaller groups within a larger room, equipped with a single overhead camera, to capture the movement of shapes on the table. At the end of the session, a summary from each group is recorded, capturing video of the table, the shapes, and the participants presenting.

In summary, from the *participant perspective,* this phase is about actively sharing situated knowledge, risks, and values that are rooted in their specific disciplinary, organizational, or lived experiences. Participants work to identify blind spots and asymmetries in understanding and begin building mutual recognition across sectors and domains. This early engagement is essential for establishing a baseline of trust and shared language, enabling productive transdisciplinary dialogue. In parallel, the *facilitator role* involves mapping the diverse knowledge systems and eliciting institutionalized logics presented by stakeholders, ensuring these are properly acknowledged and documented. Facilitators also play a critical role in surfacing underlying tensions, value conflicts, and contradictions that may otherwise remain implicit. Importantly, they need to ensure that all perspectives are treated equally, without favouring one over another. This means creating a setting where everyone's voice is heard, respected, and genuinely included from the beginning. This careful setup helps build a strong base of shared knowledge for the next steps of exploration and integration.

2.2. Phase 2 — Knowledge Exploration

The co-creation process revealed that developing integrated adaptation solutions first requires understanding stakeholders' perspectives on climate risks—along with their underlying beliefs, interests, and rationales for supporting or opposing adaptation measures. To address this, the integration of institutionalized logics theory with AI-supported techniques emerged during the discussions within the consortium as a novel diagnostic approach for identifying hidden divergences and convergences in stakeholders' values and decision-making processes. This methodological innovation constitutes the basis for the second phase of the framework, referred to as *knowledge exploration* which includes two steps: (i) analysis of the logics; and (ii) representation of findings.

a) Analysis Step: Identifying Institutionalized Logics.

We integrate AI-supported techniques with the institutionalized logics theory (see Fig. 3) to analyse the argumentative structures (Lawrence and Reed, 2020) and values (Liscio et al., 2021) expressed by researchers and practitioners. For doing this, we use Natural Language Processing (NLP) techniques, such as (1) argument mining and summarization (Van Der Meer et al., 2024a, 2024b), which seek to extracts key arguments from a discussion, (2) value extraction (Liscio et al., 2025), which recognizes values underlying arguments, (3) novelty and disagreement detection (Rosenthal and McKeown, 2015), which detects novel viewpoints and disagreements among viewpoints, and (4) perspective clustering (Vossen and Fokkens, 2022), which groups similar perspectives.

This reflection-as-research approach aims to contribute to the understanding of collaborative governance (e.g., Ansell and Gash, 2018) and to identify institutional arrangements that enhance collective capacity for integrated climate adaptation in the built environment (Red&Blue Proposal). Our analysis is based on two data sources:

- Empirical insights and experiences learned through the case study development, as reflected in the 'knowledge elicitation' phase.
- Supplementary insights from climate-related literature, news media, stakeholder publications, and other documented sources to enrich and contextualize our empirical insights.

b) Resolution Step: Representation of Findings.

This step focuses on the structured representation of findings, identifying interrelations between insights, and determining suitable integrated adaptation solutions. Examples of such representations include deliberation maps (Klein, 2021), which help visualize key patterns. Findings are then clustered based on factors such as rules and shifting frames within discourses, barriers and limitations, enablers, priorities, metrics, and strategic requirements for effective adaptation solutions. Given Red&Blue's area-based approach, these solutions have been presented to experts as adaptation scenarios to be discussed, refined, and selected collaboratively for the urban use cases in Rotterdam and Amsterdam. Additionally, we have been exploring their scalability and applicability to other

comparable neighbourhoods and cities in the Netherlands and potentially beyond.

In summary, on the *participant side*, the knowledge exploration phase involves engaging in structured dialogue to critically examine assumptions, question dominant frames, and negotiate contested concepts such as "resilience" and "value". Through these interactions, participants begin the collective process of reframing climate risks and rethinking responsibilities across sectors. *Facilitators* support this process by providing reflective tools—like shared lexicons and discourse analysis—to help participants identify patterns in reasoning and language. They mediate conversations, surface institutionalized logics, and highlight points of convergence or productive disagreement, aided by AI techniques such as argument mining and value extraction. Using a discursive database and supporting documents, they reveal deeper structures behind stakeholder positions, enabling more grounded, cross-disciplinary understanding.

2.3. Phase 3 — Knowledge Integration

The outcomes of the co-creation process and subsequent integrative forum exchanges within the consortium highlighted an urgent need to move beyond merely exploring and analyzing diverse forms of knowledge toward systematically *synthesizing* and *validating* them to enable the translation of insights into integrated solutions. Recognizing this as a crucial process in transdisciplinary knowledge co-production, we therefore embedded a distinct knowledge integration phase in the framework, comprising two interlinked steps: (i) knowledge synthesizing; and (ii) knowledge validation.

a) Synthesizing Step

This step involves the iterative process of assembling, adapting, and refining insights – generated during the exploration phase – into integrated solutions. This emerged from consortium reflections showing that alignment of language, concepts, and topical areas across disciplines and sectors was essential for joint sense-making. Partners consistently emphasized that transdisciplinary progress requires not only the generation of knowledge but also its careful assembly, translation, and alignment across different vocabularies, analytical lenses, and institutional contexts. Accordingly, this step aims to promote mutual understanding and build consensus around feasible and desirable adaptation strategies through structured reflection and feedback sessions in which stakeholders engage in safe space interactions.

Our observations from expert-focused meetings showed that participants' arguments and reflections often prompted further refinement in subsequent sessions, forming a feedback loop that continuously strengthened and harmonized the collective knowledge base. Facilitators play a key role in supporting this process by offering synthesis tools such as visual maps, conceptual frameworks, and diagrammatic models to bridge disciplinary gaps and connect diverse insights. The outcome of this step is a co-produced, intermediate

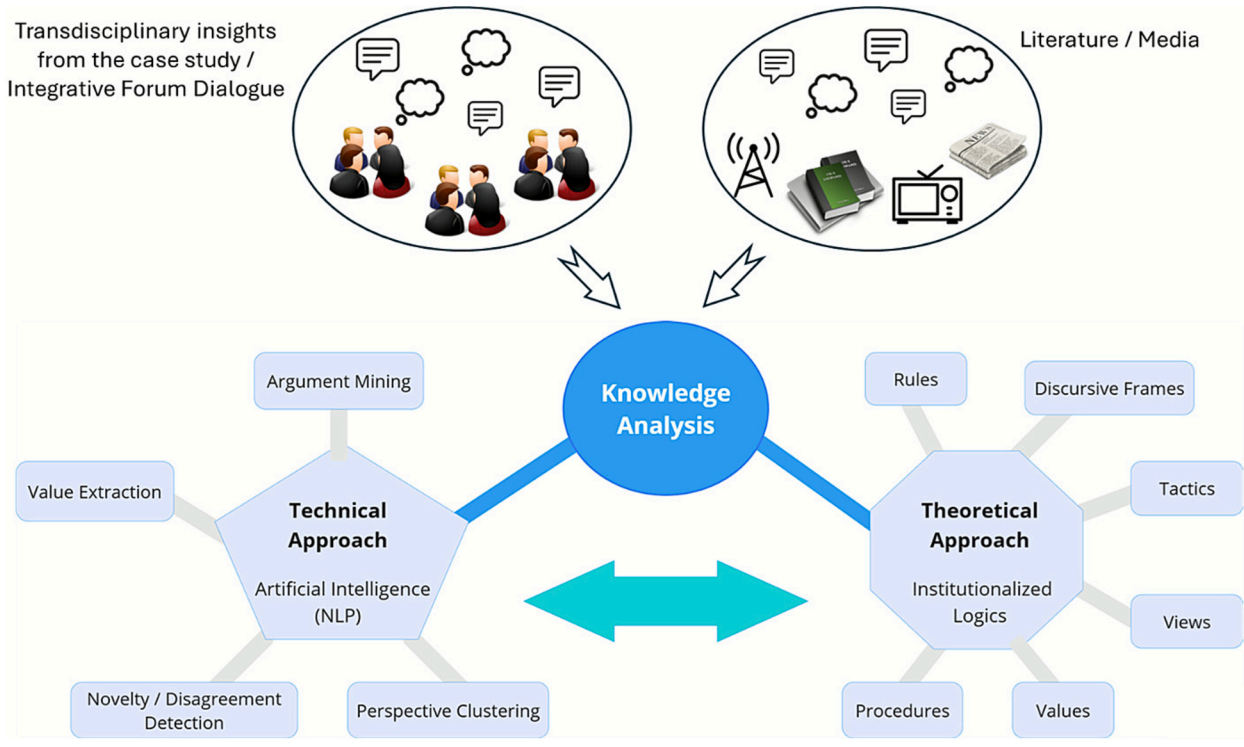

Fig. 3. Schematic representation of the 'knowledge analysis' step, integrating the theoretical approach of 'institutionalized logics' with AI-supported techniques. This process draws insights from two sources of data; a) experiential learning and transdisciplinary observations gained through framework's application to the case study, b) literature, news, and media sources.

synthesis output that captures shared frameworks, collective research questions, and integrated understandings across sectors and stakeholders.

b) Validation Step

Consortium learning experiences emphasized the necessity of verifying the relevance, feasibility, and applicability of synthesized knowledge in real-world contexts. The Red&Blue urban use cases—such as those in Amsterdam and the Greater Rotterdam Area—serve as testing grounds for the synthesized strategies, allowing assessment of their practicality under actual strategic, spatial, and social conditions. Through validation dialogues and cross-sectoral sessions, stakeholders collectively assessed intermediate synthesis outputs, testing them against practical challenges, sectoral priorities, and policy frameworks. The outcome of this empirically grounded phase is a co-produced synthesis that captures shared frameworks, collective research questions, and integrated understandings—establishing a validated knowledge base that further can support translation into actionable adaptation pathways.

In summary, for *participants*, the knowledge integration phase centres on the co-production of integrated insights, strategies, or future scenarios by combining disciplinary and sectoral knowledge revealed earlier. Through structured reflection and feedback sessions, participants are encouraged to critically review and jointly validate the synthesized knowledge, engaging in dialogue to ensure that all perspectives are acknowledged. This process also prompts individual and collective reflection on how understanding, roles, or positions may have shifted through the integration process. In parallel, *facilitators* play a key procedural role in structuring and enabling this integration. They present synthesis tools—such as visual maps, conceptual frameworks, and diagrammatic representations—to help clarify and connect insights. Importantly, they mediate and scaffold validation sessions across divergent logics and stakeholder interests, ensuring that integrated solutions are both meaningful and actionable. They also produce synthesized intermediate output for validation purposes.

2.4. Phase 4 — Knowledge Transformation

Through iterative dialogues among researchers, financial institutions, public authorities, and other practitioners, it became evident that the value of transdisciplinary collaboration for addressing climate risks ultimately depends on its capacity to inform concrete adaptation pathways and decision-making processes.

This has led us to embed the final phase in the framework focusing on operationalizing validated insights by co-developing desirable, context-specific, and integrated adaptation solutions that align with institutional, spatial, and temporal realities. The integrative forum's discussions revealed that such solutions differ in their expected impact and efficiency depending on the type of physical climate risk (e.g., heat stress, flooding), their applicability across various scales (asset, neighborhood, regional), and the resilience capacity of the systems involved. Moreover, reflections during the integrative forum highlighted that proposed strategies must also address multi-dimensional challenges—such as social equity, financial feasibility, and environmental sustainability—to ensure their legitimacy and applicability across sectors.

For *participants*, this phase means re-interpreting the shared outcomes through the lens of their own institutional mandates, constraints, and timelines. They are tasked with translating the integrated knowledge into silo-relevant language, aligning it with organizational priorities, and determining feasible actions. This process involves negotiating how collective insights inform specific decisions, adjusting them to fit within existing governance or operational frameworks, and—crucially—committing to implementation, establishing feedback mechanisms, or initiating further iterations where needed. *Facilitators* play a vital role in preserving shared understanding as it re-enters institutional siloes. They adapt insights to each sector's logic and constraints, ensuring that ideas are not lost or distorted. By monitoring uptake and drift, facilitators maintain coherence, identify gaps between intent and practice, support adaptive learning, and feed insights back into collaboration. They also communicate outcomes more broadly, connecting them to strategic or policy debates. This phase highlights transformation as a negotiated, reflexive process—not just the end point of this process, but key to driving real-world change.

3. Results

Application of the KPCRM framework in the Red&Blue case study revealed several key transdisciplinary challenges in facilitating knowledge production for integrated climate risk management. Mehvar et al. (2025) presented some preliminary observations including barriers such as language issues, mismatched interests, trust issue, and imbalanced institutional engagement capacity. Here, we reflect on when—during which phase of the framework—these challenges raised, and further present complementary findings, including additional barriers that emerged throughout different phases of application.

Based on these findings, we propose key enablers and recommendations to address the challenges and to enhance facilitation of transdisciplinary knowledge production in the context of climate adaptation that can possibly be applicable in any other transdisciplinary work (see Fig. 4). While these findings stem mainly from the case study application, we situate them within broader scholarly debates by referencing supporting insights from prior transdisciplinary studies.

3.1. Challenges of Transdisciplinary Knowledge Production

3.1.1. Phase 1 — Challenges of Knowledge Elicitation

- Language Barriers

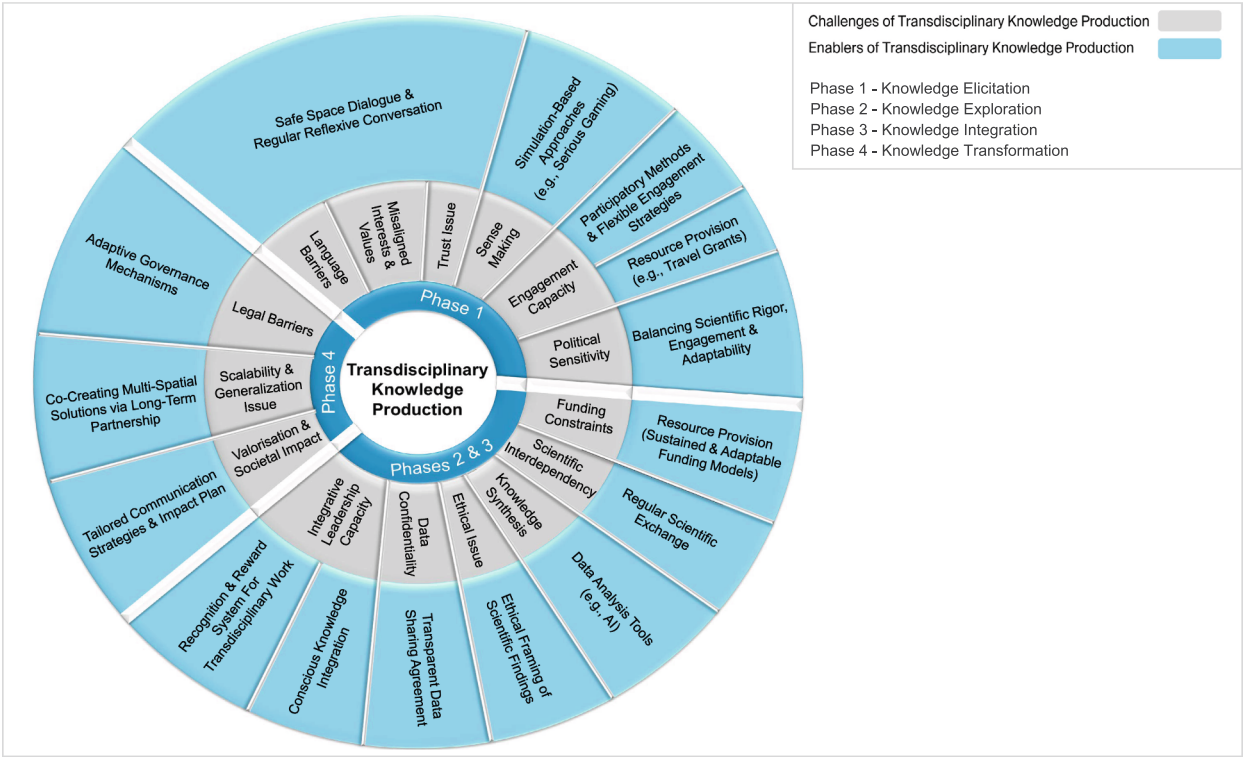

Fig. 4. Results of the application of the KPCRM framework to the Red&Blue case study, highlighting the challenges (in grey) and enablers (in blue) of transdisciplinary knowledge production identified across different phases of the framework's implementation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Integrative forum interactions highlight differing interpretations of key concepts and terminologies due to variations in disciplinary backgrounds, knowledge traditions, professional cultures, and methodologies. This reflects language and translation challenges (Liu et al., 2019; Scholz et al., 2024), where meanings shift depending on context. Examples include terms like inter/multi/transdisciplinary, risk, and resilience.

- Misaligned Interests and Values

Knowledge exchanges show diverging interests, values, and priorities between scientists and practitioners as similarly reflected by Bergmann et al. (2021). For example, we found that real estate investors focus on asset-level climate risks, while urban planners prioritize broader spatial assessments. Stakeholders also differ in their scale of action, from national policies to international investment goals. Additionally, conflicting values pose challenges, as municipalities prioritize socio-economic risks and climate justice, whereas investors primarily focus on financial risks and returns on their investments.

- Trust Issue

We observe that trust issue can significantly hinder transdisciplinary collaboration, as some stakeholders are reluctant to fully share their insights or engage openly in knowledge exchange (Daniels et al., 2020). This hesitation often arises due to conflicting values, data sensitivity, or institutional representation. For example, during our first-year exchanges on urban climate issues in selected neighbourhoods particularly exposed to physical climate risks (e.g., flooding, heat stress, and land subsidence), we observed a degree of hesitancy among participants to disclose plans and share insights, which at times can imped meaningful knowledge co-production.

- Sense Making

Stakeholders dialogue underscore sense-making as a critical transdisciplinary challenge in knowledge elicitation relating to how stakeholders perceive and understand climate risk, their roles, and responsibilities when dealing with it. We realized that this challenge goes beyond language barriers, which primarily involve differences in terminology. Stakeholders need to continuously navigate and respond to uncertain climate events, likely physical impacts, policy shifts, and institutional reforms, highlighting sense-making a key factor in shaping adaptation strategies.

- Engagement Capacity

We observe imbalances in institutional capacities among consortium members, with some participating less frequently in knowledge exchange activities. This challenge arises from institutional constraints, such as the limited financial capacity of non-profit organisations compared to larger financial institutions. Our research in Amsterdam and Rotterdam highlights challenges in fostering engagement, particularly in building case study collaborations and strengthening relationships with local governments. Such challenges reflect the coexistence of differing climate risk strategies and uneven institutional commitment observed across political, strategic, and project levels. This was also highlighted by Jellason et al. (2020) as a barrier to inclusive adaptation processes.

- Political Sensitivity

We find that stakeholders dialogue on climate risks and adaptation can become politically sensitive, particularly at the neighbourhood level, due to implications for resource allocation, land use, and social equity. Our urban use cases development show that balancing competing interests among public and private stakeholders adds complexity, as decisions on real estate, zoning, and financial incentives create winners and losers, often sparking resistance. As another example, our finance-policy discussions within the consortium revealed that adaptation requires long-term commitments and upfront costs, which may conflict with short-term political cycles and priorities.

- Recording and Transcribing Issues

We recognise that the effectiveness of AI-supported knowledge elicitation depends on participants' willingness to be recorded, which varies with discussion sensitivity, trust in data management, and group composition. Additionally, our experiment with AI transcribing tools shows limitation of transcription quality, due to using a single microphone, which made it hard to capture all voices clearly. While individual microphones could improve clarity, they require more setup, technical familiarity, and participant cooperation, which can be challenging.

3.1.2. Phases 2 and 3 — Challenges of Knowledge Exploration and Integration

- Integrative Leadership Capacity

We recognize that it is crucial to have integration expertise and leadership capacity to effectively analyse and synthesize knowledge across disciplines (Hoffmann et al., 2022). Traditional academic roles are often discipline-specific, lacking the skills required for cross-sectoral collaboration and knowledge integration. In Red&Blue, we observe this limitation underscoring the need to build both individual and collective capacity for structured knowledge integration and collaboration.

- Data Confidentiality

Wo notice that data confidentiality concerns pose a major challenge to transdisciplinary knowledge integration by restricting data sharing and collaborative analysis (Hermans et al., 2022). We observe this issue during expert-focused meetings where some stakeholders show hesitation to disclose climate risk maps and real estate exposure data due to portfolio confidentiality and institutional policies. This issue restricts knowledge elicitation, but mainly data analysis, challenging the development of standardized and integrated climate risk assessments.

- Ethical Issue

We recognise ethical challenges in transdisciplinary knowledge integration which can lead to unintended consequences. For example, our neighbourhoods-focused discussions revealed that territorial stigmatization may occur when highlighting climate vulnerabilities—such as flood risk or heat stress—reducing an area's attractiveness for investment, development, or residency. Additionally, climate gentrification may happen when adaptation investments increase property values, forcing lower-income residents out of climate-resilient areas due to rising costs.

- Knowledge Synthesis

Our observations highlight that knowledge synthesis faces challenges such as inconsistent terminology, disciplinary silos, and communication gaps that hinder integrating diverse insights. Inclusivity appears to be difficult, as dominant voices often overshadow others. We notice that synthesizing complex insights also requires balancing rigor and accessibility, while climate risk uncertainty demands flexible, adaptive approaches suited to varying expertise and priorities.

- Scientific Interdependency

Our analysis reveals that scientific interdependency challenges knowledge integration, as research teams rely on each other's

progress and results. Differences in research focus, methodologies, and timelines can create friction, as observed for example in Red&Blue's research being conducted by PhD researchers, physical climate risk insights are needed before asset value-at-risk mapping can advance. Knowledge integration teams also depend on domain researchers for the timely exchange of findings and data, yet delays have been a recurring issue.

- Funding Constraints

We note that research funding often falls short for transdisciplinary knowledge integration, which is time- and resource-intensive. Red&Blue highlights the need for sustained support for researchers, engagement, and co-production. However, short-term funding models may lack adaptability, limiting long-term collaboration and integration.

3.1.3. Phase 4 — Challenges of Knowledge Transformation

- Legal Barriers

We find that translating integrated knowledge into policy is often constrained by legal and regulatory challenges related to land use, liability, building codes, compliance, property rights, and financing mechanisms. Empirical insights from our integrative forum discussions highlighted ongoing tensions regarding roles and responsibilities in creating climate-resilient neighbourhoods. For example, participants emphasized that zoning and spatial planning laws need to explicitly incorporate climate risk considerations, while liability for damages in vulnerable areas requires clearer legal definitions and allocation of responsibility across public and private actors. Similar legal-institutional constraints on adaptation have been noted in policy integration studies (see O'Neill et al., 2022; De Jong et al., 2019).

- Scalability and Generalization Issue

The urban use case discussions with our practice partners reveal that scalability and generalizability of the integrated climate risk management strategies can become problematic, as effective implementation of the solutions requires addressing spatial scale issues when applying validated insights, proposing adaptation measures, and informing decisions. For instance, aligning urban and delta-level actions raises questions about flood safety systems. Knowledge gaps also hinder linking physical risks with socio-spatial vulnerabilities—crucial for coordinated stakeholder action.

- Valorisation and Societal Impact Issue

As similarly highlighted by Pereira et al. (2020), our observations reveal that communication and valorisation challenges hinder societal impact in transdisciplinary collaboration, contributing to the "knowledge-action" gap. Accessing integrated knowledge remains difficult, as academic incentives favour publications over real-world use. We realize that long policy timelines and unclear impact metrics make measuring societal outcomes hard, weakening the case for sustained investment in transdisciplinary adaptation and policy integration.

3.2. Enablers of Transdisciplinary Knowledge Production

3.2.1. Phase 1 — Enablers of Knowledge Elicitation

- Safe Space Dialogue and Regular Reflexive Conversation

We find that establishing a safe space for stakeholders to openly share their insights, interests, concerns, and expectations is essential for a successful knowledge production process (see Daniels et al., 2020). Regularly facilitated reflective conversations within the Red&Blue "Integrative Forum'' proved to be effective in fostering mutual understanding of diverse institutional and disciplinary perspectives, enabling negotiation and consensus-building. We note that continuous reflection and feedback in the knowledge elicitation phase significantly enhance this alignment. However, achieving this requires sustained dialogue and multiple rounds of iteration. We recognise that this process is particularly critical for addressing challenges like language barriers, conflicting values and interests, and trust issue.

- Simulation-Based Approaches

Simulation-based approaches, especially serious gaming (Hermans et al., 2022; Gaete Cruz, 2023), can effectively address sense-making among stakeholders. In the knowledge elicitation phase, engaging actors like governments and developers in interactive scenarios helps clarify climate risks, roles, and adaptation complexities. In Red&Blue, such simulations enable exploration of trade-offs, outcome assessment, and solution negotiation, supporting more informed decisions.

- Shape Language Method

Our experience with the 'Shape Language' method, which enables communication using shapes and space instead of just words (see https://www.vormtaal.com), demonstrated its effectiveness in facilitating clearer and more efficient discussions, as the shapes being assigned meaning by the participants tend to reduce the amount of repetition of information during the discussion. It also helps participants remember the content of the meeting better.

- Participatory Methods and Flexible Engagement Strategies

Participatory methods enhance trust and engagement in transdisciplinary collaboration by promoting inclusivity, reducing institutional disparities, and ensuring balanced participation. Flexible strategies—like co-creation workshops (potentially using haptic tools), knowledge-sharing sessions, and rotating facilitation—support meaningful stakeholder input. The Red&Blue three-layer engagement and impact plan illustrates how such approaches foster sustained participation, stronger relationships, and co-produced actionable knowledge.

- Resource Provision

It is revealed that financial support, such as travel grants and targeted funding, can reduce barriers for under-resourced stakeholders, promoting more equitable participation in knowledge exchange activities (phase 1). This helps sustain collaboration, balance power dynamics, and prevent private sector dominance. Sustained and flexible funding models further build trust, support inclusivity, and enable smooth, adaptive knowledge integration throughout the process (phase 3).

- Balancing Scientific Rigor, Engagement and Adaptability

We find that scientific rigor enhances neutrality and credibility in climate adaptation by grounding knowledge in evidence-based, transparent methods, limiting political influence. Inclusive engagement, as practiced in Red&Blue through structured dialogues and co-creation, helps prevent dominance by any one group. Integrative forum discussions highlight how adaptive governance supports flexibility, iterative learning, and policy adjustment while staying aligned with long-term goals. These approaches depoliticize knowledge production, build trust, and improve the relevance of climate risk management strategies.

3.2.2. Phases 2 and 3 — Enablers of Knowledge Exploration and Integration

- Recognition and Reward System for Transdisciplinary Work

We note that limited integrative leadership can hinder transdisciplinary collaboration, emphasizing the need for recognition and reward systems that value such work (Scholz et al., 2024). Effective knowledge integration requires institutional support to sustain impact-driven activities. Research evaluation should go beyond traditional metrics to acknowledge transdisciplinary collaboration, leadership in collective knowledge production, and engagement with societal stakeholders.

- Conscious Knowledge Integration

We find that conscious knowledge integration—a deliberate process combining diverse perspectives through interaction, leadership, and iterative collaboration—is vital for addressing limited integrative leadership in transdisciplinary work. Cultivating such leadership among scientists and societal partners enables alignment through dialogue, collective decision-making, and shared learning. More than merging knowledge, this approach guides effective integration, ensuring active stakeholder participation and revisiting insights over time to support co-creation. In Red&Blue, Gluon knowledge integration specialists play a key role as brokers, facilitating learning cycles between academia and practice, and connecting problem analysis with impact pathways (see Buser and Schneider, 2021; Mehvar et al., 2025).

- Transparent Data Sharing Agreement

From the outset of the Red&Blue co-creation process, transparent data-sharing agreements have proven essential for effective climate risk management. Clear terms on access and usage help navigate institutional policies and confidentiality concerns. Forum discussions emphasized how data anonymization protects sensitive information while maintaining its analytical value. Regulatory incentives, legal safeguards, and transparent agreements further encourage responsible data sharing, reducing fears of competitive or legal risks in transdisciplinary collaboration.

- Ethical Framing of Scientific Findings

Our observations show that ethically framing scientific findings is vital in transdisciplinary climate adaptation to tackle socio-economic risks like territorial stigmatization, climate redlining, and gentrification. Addressing distributional aspects of climate risk helps mitigate these impacts. A holistic approach—balancing ecological, technical, financial, and social factors—aligns scientific independence with societal needs. Proactive community engagement and policy safeguards are key to preventing inequalities and

ensuring equity and inclusivity in neighbourhood-level adaptation and resilience efforts.

- Data Analysis Tools: Application of AI Techniques

We recognize that AI-supported data analysis tools like NLP play a vital role in transdisciplinary collaboration, policy development, and decision-making. In Red&Blue, these tools effectively (though limited by factors like recording context and dialects) translate dialogue into text, synthesize information, and integrate diverse datasets from forums and literature. They help extract institutionalized logics on climate adaptation, identify climate projections, socio-economic indicators, geospatial data, and generate predictive models for assessing vulnerabilities, risks, and adaptation solutions, supporting the knowledge resolution phase.

- Regular Scientific Exchange

Regular academic progress meetings and knowledge exchange sessions, like Red&Blue's monthly labs, help overcome scientific interdependency challenges during the knowledge integration phase. These structured interactions promote alignment, coordination, and timely sharing among research teams by clarifying dependencies, expectations, and timelines. This reduces delays from disciplinary differences and ensures prompt exchange of critical insights, enabling smoother transitions between research phases and effective knowledge integration.

3.2.3. Phase 4 — Envisioned Enablers of Knowledge Transformation

The transdisciplinary knowledge co-production process continues to be developed within the Red&Blue consortium. The subsequent phase, which is currently underway but still ongoing, has identified a set of enabling conditions that are necessary to translate integrated knowledge into practice. Because this phase has not yet been fully implemented, these findings should be interpreted as envisioned enablers rather than as applied solutions within the case study.

- Adaptive Governance Mechanisms

Our empirical observations highlight adaptive governance (Ansell and Gash, 2018) as crucial for overcoming legal barriers in real estate climate risk management. Red&Blue expert meetings show that better cross-sector coordination—like integrating climate risk data into zoning and aligning land-use laws—enhances urban resilience. Additionally, clear liability definitions are vital for assigning responsibility and enforcing adaptation. Proactive legal frameworks enable early climate adaptation, reduce disputes, and ensure regulatory stability. Well-defined legal pathways for compensation and compliance are also key to resolving property rights issues in retrofitting or relocation.

- Co-Creating Multi-Spatial Solutions via Long-Term Partnership

We recognise that sustained engagement between researchers and practitioners helps address spatial scale challenges in transdisciplinary collaboration by aligning urban climate risk management with broader delta system actions. These partnerships improve multi-scalar risk assessments, linking physical risks with socio-spatial vulnerabilities. Continuous co-creation among public, private, and civic actors ensures adaptation strategies are scalable, context-sensitive, and well-integrated into governance, enhancing the effectiveness of climate adaptation policies.

- Tailored Communication Strategies and Impact Plan

The Red&Blue co-creation process highlights the need for tailored communication to bridge the knowledge-action gap. Stakeholder-specific methods—like policy briefs for decision-makers, risk visuals for investors, and workshops for communities—enhance engagement and impact. Multi-channel dissemination via digital platforms, roundtables, and knowledge brokers expands outreach. Aligning academic incentives with societal impact through co-authored reports and urban living labs ensures research informs policy. Together, these strategies make scientific insights accessible and actionable, supporting long-term transformation in real estate climate risk management.

4. Discussion

The KPCRM framework introduced in this study serves as a methodological tool for facilitating transdisciplinary knowledge production, and demonstrates its application for developing integrated climate risk management strategies, as explored in the Red&Blue case study. It builds on insights from the literature review, alongside empirically grounded yet practice-based insights generated through Red&Blue, including stakeholder engagements, co-creation activities, and integrative forum discussions—a preliminary version of which is presented by Mehvar et al. (2025). This methodological design reflects the transdisciplinary ideal of combining *generalizable method* with *context-specific learning*.

Drawing on recent scholarship on transdisciplinary knowledge production, the framework was first designed to conceptualize how integrative knowledge production processes unfold—from initial problem framing to collaborative synthesis and transformation. In doing this, we synthesized theoretical insights from the literature on knowledge co-production, into a coherent stepwise framework.

The Red&Blue programme, situated in the Dutch delta, then served as a living laboratory in which these theoretical components were operationalized and examined through experiential learning. As a collective inquiry based on jointly formulated research questions, Red&Blue provided a setting where diverse disciplinary and societal actors could enact, test, and refine the framework's principles in real time. Observing how these theoretical dimensions "showed up" in practice—through stakeholder dialogues, integrative forums, and iterative reflection cycles—enabled the research team to trace the translation from conceptual design to practical application. This process not only grounded the framework empirically, but also fed back new insights that informed its further refinement and contextual adaptation to the Dutch climate risk management landscape.

The empirical findings highlight that addressing complex climate risks in the Netherlands requires shifting from fragmented risk management approaches toward integrated strategies that connect public, private, and civic actors across multiple spatial scales. Here, integration refers not only to bringing diverse perspectives together, but also to ensuring their substantive incorporation into decision-making—evident in the extent to which perspectives are considered equally, the depth of stakeholder engagement, shared ownership of outputs, and how these dynamics shape outcomes.

These insights played a central role in shaping and iteratively refining the framework during the first 2.5 years of Red&Blue, informing our core research question: How can transdisciplinary knowledge production be effectively facilitated for integrated climate risk management? Given that Red&Blue is ongoing, the empirical insights presented in this article should be understood as practice-based and formative rather than fully triangulated. Notably, their purpose is to guide and progressively refine the framework, rather than to serve as definitive empirical validation.

The KPCRM framework is novel in offering a structured, step-wise methodology for transforming transdisciplinary knowledge into actionable insights and integrated solutions for decision-making. Its integrated knowledge analysis approach combines the theoretical concept of institutionalized logics with AI-supported techniques, enabling systematic analysis of stakeholders' perceptions, institutional norms, and actions in managing climate risks.

The framework offers both participants and facilitators in the knowledge co-production process a clearer understanding of how it functions in practice according to their respective roles, by framing a two-dynamic model of knowledge integration. The first focuses on the collective process that participants experience, which unfolds through four key phases: (1) knowledge elicitation, (2) exploration and sense-making, (3) integration, and (4) transformation. The second dynamic outlines the procedural steps undertaken by integration experts to facilitate and analyze the process effectively. Corresponding to the above-mentioned four phases, these steps include: (i) ensuring all relevant knowledge and stakeholders are identified and acknowledged, (ii) analyzing emerging knowledge using institutionalized logics combined with AI-supported techniques, (iii) integrating knowledge by supporting participants in synthesizing diverse insights, and validating the synthesized knowledge with the group to ensure all perspectives are recognized, and (iv) transforming the integrated knowledge into practice by developing integrated strategies and redefining meaning through relational understanding, and through translating this integrated knowledge back into actionable language and steps tailored to each stakeholder's domain.

While the framework was developed through a formative and practice-based empirical insights, several measures were taken to enhance its robustness, validity, and reproducibility.

Stakeholder selection was guided by transparent criteria to ensure representation across relevant institutional, disciplinary, and sectoral domains—ranging from finance actors to urban planners, flood risk experts, municipalities, ministries, and other stakeholders. This selection is mainly based on the relevance of the expertise to the aim/topic of the session (e.g., municipalities are often invited for urban use case workshops and exchange sessions; similarly, banks, real estate investors and insurers are engaged for the climate finance discussions and topics like adaptation costs and benefits).

Engagement consistency across the three layers was maintained through structured interaction formats (e.g., monthly labs across research community; annual symposium for the whole consortium; regular urban use-case workshops organized by use case team of researchers inviting selected societal partners; bilateral exchanges across research teams, and between researchers and practitioners). Standardized documentation practices such as meeting summaries, discussion notes, and synthesis outputs supported continuity across these interactions and facilitated follow-up conversations and reflective learning.

Potential bias in the interpretation of qualitative data was mitigated by establishing a shared data repository across research teams, collaboratively handling data, and cross-checking emerging insights. This occurred, for example, during monthly lab sessions where researchers regularly shared, discussed, and reflected on their data collection, analysis, and findings. In addition, the use of iterative feedback loops enabled continuous verification of the relevance and applicability of insights, thereby enhancing both the internal validity and the external transferability of the framework.

The challenges identified in this study align with broader issues noted in transdisciplinary research, particularly the difficulty of integrating diverse perspectives, methodologies, and disciplinary languages (Lang et al., 2012; Mauser et al., 2013). Our findings extend this body of work by demonstrating how structured, iterative dialogues within a conscious designed engagement setting can mitigate knowledge fragmentation and enhance practical relevance—an area that remains underdeveloped in transdisciplinary climate research.

While many transdisciplinary approaches emphasize dialogue facilitation and shared framing (e.g., Liu et al., 2019), the KPCRM framework stands out by integrating both dialogue facilitation and empirical testing in real-world contexts. Unlike traditional models that prioritize either scientific rigor or stakeholder participation, KPCRM offers both through its three-layer science-practice engagement and impact plan. By combining the conceptual lens of institutionalized logics (Thornton et al., 2012) with AI-assisted techniques, the framework fosters trust-building, reduces language barriers, and supports adaptive, and inclusive integration processes.

Moreover, the framework contributes to addressing a critical gap in literature: the limited application of transdisciplinary co-

creation approaches in climate adaptation (Taylor et al., 2023). Its knowledge elicitation phase—particularly through the integrative forum dialogues—offers a replicable model for embedding diverse scientific and societal actors in collaborative knowledge production. This approach is essential for fostering ownership and increasing the uptake of adaptation strategies, as emphasized by Jellason et al. (2020). Our findings also highlight that successful knowledge production relies not only on transdisciplinary processes and tools, but also on integrative leadership to guide co-creation and foster collaboration across institutional and disciplinary boundaries (Bergmann et al., 2021).

The KPCRM framework proved effective in identifying both barriers and potential enablers to transdisciplinary knowledge production, as illustrated in Fig. 4. It identified key challenges encountered during various phases of implementation and proposed solutions to address them. Notably, disciplinary silos, power dynamics, engagement capacity, and data accessibility emerged as significant barriers to knowledge co-production. However, structured stakeholder engagement and the creation of a 'safe space' for open dialogue showed to be critical in bridging divides and fostering cross-sector collaboration. Additionally, the framework supports iterative learning, enabling continuous refinement of insights and underscoring the importance of adaptive and reflexive governance for long-term collaboration. The presented enablers were categorized based on their emergence and their direct impact on addressing specific challenges. For example, the integrative forum—described as a "safe space for dialogue"—was initially designed to support knowledge elicitation (phase 1), addressing trust and language barriers. However, over time, it also proved effective in tackling scientific interdependencies during knowledge exploration (phase 2).

In terms of applicability, the framework was designed as a generalizable methodological tool for transdisciplinary knowledge production. The underlying challenges and enablers such as safe-space dialogue, iterative feedback loops, AI-assisted knowledge analysis, and integrative leadership are viewed as transferable principles that can guide science–practice collaboration beyond the Dutch context in other urbanized, climate-vulnerable settings that require coordinated adaptation across science, policy, and practice.

However, several of the empirical findings and implementation experiences reflected in this article are derived from the case study and thus are context-specific to the Dutch delta area. The challenges about climate risk management reflect the Netherlands' particular institutional, legal, and geographic conditions. These include, for example, issues surrounding spatial planning limitations, housing shortages, substantial retrofitting required in the large part of the existing cities to become climate-adaptive, and so on. Additionally, contextual factors such as the new Environmental Act, the "Water and Soil as Guiding Principles" directive, and sensitivities around data sharing within the Dutch financial sector further characterize landscape of climate risk management in the Netherlands. Other examples include the interplay between urban-scale adaptation and delta system-level action, the country's strong tradition of institutionalized water management, the need to involve financial actors in delta-related knowledge production, and unequal engagement capacities across institutions—ranging from political and strategic to project levels and among different municipal departments—all illustrate how these insights are embedded within the distinctive governance and policy context of the Netherlands.

In developing the framework, some limitations must be acknowledged. While the empirical insights underpinning the framework are practice-based and formative, this partial validation also reveals important methodological and epistemic limitations. **First**, because the Red&Blue programme is still at its midpoint, the evidence informing the framework primarily captures *process-level learning* – how knowledge is co-produced – rather than *outcome-level impacts* of integrated adaptation strategies. This means the framework's effectiveness in translating shared understanding into tangible policy or investment decisions has not yet been assessed. **Second**, the reliance on reflective, experiential insights and limited data triangulation constrains the generalizability of the findings, even though such interpretive methods are intrinsic to transdisciplinary inquiry. **Third**, stakeholder hesitancy around audio recording reduced the number of large-scale expert meetings, resulting in a more limited data for AI-based analysis. However, secondary sources, including literature and publicly available publications, provided valuable complementary insights. **Fourth**, institutional constraints, such as restricted access to sensitive data and uneven engagement capacities across partners also limited the completeness of the empirical base.

The next phase of Red&Blue will directly address these limitations. As the consortium consolidates knowledge integration and enters the *knowledge transformation* phase, the framework will be applied within urban use cases to test how integrated knowledge informs design, policy, and financial decisions. Comparative analyses across case studies will allow cross-case triangulation and assessment of how the framework performs under varying institutional and data conditions. In parallel, closer collaboration with municipalities and financial partners will help overcome current information barriers and produce richer, multi-source datasets for evaluation. This expansion from process-focused to outcome-oriented analysis will strengthen both the empirical validation and methodological robustness of the KPCRM framework, advancing it from a formative prototype to a fully tested model for integrated climate risk management.

5. Conclusion

This article presents the KPCRM framework—a structured, phased methodology that supports transdisciplinary knowledge production for integrated climate risk management. Its application in Red&Blue demonstrates how the framework bridges institutional and sectoral divides, across the phases of knowledge elicitation, exploration, integration, and transformation.

A key contribution of the framework lies in combining institutionalized logics theory with AI-supported techniques in the knowledge exploration phase. This approach helps systematically identify stakeholder perspectives and underlying rationales strengthening mutual understanding and supporting strategic alignment across sectors.

The findings emphasize that successful transdisciplinary knowledge production requires more than structured steps; it demands an adaptive, and iterative process. As the Red&Blue program evolved, the framework was shaped by stakeholder needs and emerging contextual dynamics. Safe space dialogue, participatory methods, and integrative leadership were central to building trust and shared

ownership.

The KPCRM framework also provides a practical pathway for operationalizing transdisciplinary collaboration by guiding the co-creation of context-specific, integrated, and actionable strategies. The Red&Blue case study identifies key enabling conditions for effective knowledge production, including sustained engagement, iterative feedback loops, institutional support, and clear facilitation roles. These support overcoming barriers such as siloed practices, misaligned interests, and power imbalances among actors.

While the case study's current stage limited the assessment of long-term societal impacts, the framework offers a strong foundation for future applications and potential scaling beyond real estate and infrastructure sector. Testing the framework in varied urban and thematic contexts will be key to fully validate its adaptability and generalizability. Moreover, emerging advancements in AI and digital decision-support tools offer promising opportunities—particularly in the knowledge exploration phase—to enhance the framework's functionality and impact.

In conclusion, the authors emphasize that without intentionally designing methodologies for knowledge production, we risk reinforcing the very silos we claim to overcome. The KPCRM framework offers a promising methodology for bridging knowledge silos, enabling cross-sectoral learning, and co-production of transformative solutions that support more integrated, equitable, and informed climate adaptation strategies in the built environment.

Ethics Approval

Ethics approval was not required for this study.

CRediT authorship contribution statement

Seyedabdolhossein Mehvar: Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anne Bruggen:** Writing – review & editing, Methodology, Investigation, Formal analysis, Conceptualization. **Pradeep Murukannaiah:** Writing – review & editing, Validation, Supervision, Methodology. **Catholijn Jonker:** Writing – review & editing, Validation, Supervision, Methodology. **Zac Taylor:** Conceptualization, Funding acquisition, Project administration, Supervision, Resources, Formal analysis, Methodology. **Tom Daamen:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

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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

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Data availability

Data will be made available on request.

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Further reading

Red&Blue: Real Estate Development & Building in Low Urban Environments. A transdisciplinary research agenda for a resilient Dutch delta. https://redblueclimate.nl.