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Knowledge diversity for climate change adaptation: A social-ecological-technological systems (SETS) approach to mental models

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ABSTRACT

As climate-driven extreme weather events continue to intensify, risk mitigation and governance are a critical aspect of urban climate change adaptation. Interdisciplinary knowledge integration is critical in order to account for varied perspectives related to the impacts of extreme weather events on urban systems. Despite advances made to integrate different strands of knowledge through systems-based approaches, few methods exist to contextualize and analyze the diversity of the knowledge being integrated. Assessing knowledge diversity exposes varying ways in which stakeholders identify and problematize the impacts of extreme weather events, uncovering knowledge gaps as well as dominant knowledge framings that might bias and/or hinder risk governance processes. This study presents a novel methodology that integrates a mental models approach with the social-ecological-technological systems (SETS) framework to assess and compare the perceptions of individual stakeholders on the impacts of extreme weather events on an urban system. By classifying system components and interactions into social, ecological, and technological domains, mental models enable the visualization of knowledge diversity, as well as the identification of potential gaps and silos in stakeholder understanding. The methodology is applied to New York City, engaging 20 expert stakeholders from diverse disciplines and sectors involved in mitigating the impacts of extreme precipitation. Findings reveal significant variability in how stakeholders emphasize SETS domains and interactions. By supporting more holistic and inclusive co-production processes, this approach provides a theoretical and empirical foundation for addressing the multifaceted challenges posed by climate change in urban environments.

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1. Introduction

Climate-driven amplification of intensity and frequency of extreme weather events poses significant threats to people and nature [1]. Cities around the world face particularly high risks, as they concentrate people, infrastructure, and economic activity [2–5]. Consequently, mitigating climate-induced risks is considered a cornerstone of urban adaptation planning [6–8].

Climate adaptation planning requires a multi-faceted understanding of risk, defined as the potential for adverse consequences resulting from current or future combinations of exposure and vulnerability to a hazard [1,9]. Understanding the direct and indirect impacts of climate change is a foundational challenge encountered by decision-makers involved in risk-based adaptation planning [10]. Thus, integrative approaches to problem definition are key for ensuring effective adaptation planning processes that consider the spread of climate impacts across a wide variety of sectors and scales [11–13]. This integration, however, implies dealing with the fact that different stakeholder groups may differ in their perceptions and values about complex problems [14,15]. Tackling the complexity of urban systems for climate adaptation requires not only diverse knowledge, but also a structured way to analyze how different forms of knowledge perceive climate risks across social, ecological, and technological domains, thus shaping adaptation decisions. This aligns with the concept of Knowledge Systems (KS), which encompasses the structures, processes, and social norms shaping the creation and integration of knowledge into decision-making [16–18]. Through KS, knowledge diversity can be situated within broader institutional and governance landscapes, emphasizing the importance of integrating diverse knowledge to overcome epistemological silos and support inclusive adaptation planning.

Besides the wide variety of impacts experienced by cities, effective adaptation planning must account for the interconnected nature of urban systems [19–22]. Systems approaches are considered useful for tackling the complexity and interdependencies of climate change adaptation in cities [23–28]. Depending on the focus and the challenge at hand, urban resilience and infrastructure systems have been approached through social-ecological systems (SES) or socio-technological systems (STS) perspectives [21]. Aiming to integrate both approaches into a more holistic conceptualization, urban environments have more recently been framed as interdependent Social-Ecological-Technological Systems (SETS) [20,21,29]. SETS are framed as an entanglement of social, ecological, and technological domains (Fig. 1) that must be recognized as interlinked, or "coupled" rather than as three separate subsystems [30]. Considering the couplings between SETS domains is crucial to enable sustainable urban transformations that maximize synergies and minimize trade-offs across domains [5], account for cascading impacts [31], and reduce the risk of maladaptation [32,33]. For instance, smart-city approaches failing to couple with the social and ecological domains tend to over-rely on digital and infrastructural solutions while overlooking critical issues such as inequality, environmental justice, and environmental stewardship [34]. Similarly, the capacity of urban ecosystems and nature-based solutions to provide ecosystem services relevant to climate adaptation is heavily moderated by social and technological factors in addition to ecological conditions [35,36].

Most empirical applications of SETS to urban climate risks approach the integration of the three different domains through spatially explicit, quantitative analyses that combine pre-identified social, ecological, or technological indicators [37–39]. Accordingly, SETS visualization has also focused on data visualization platforms where spatial layers are used to represent either system domain (S, E, or T) [13,40]. While useful for visualizing the heterogeneous distribution of S, E, or T components and their spatial interactions, these

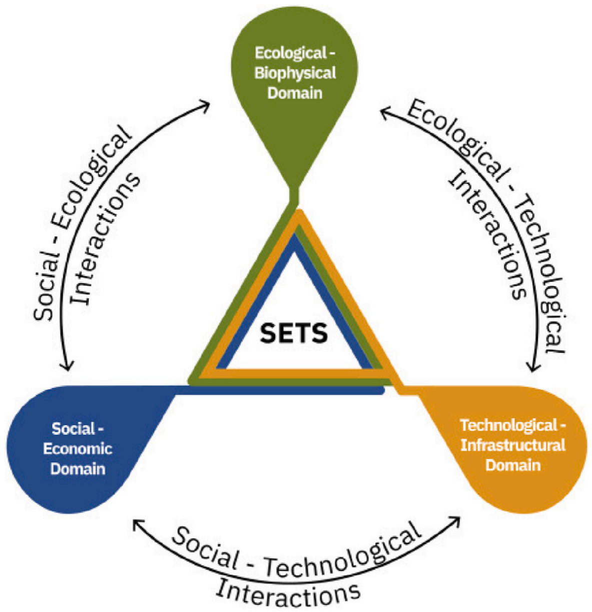

Fig. 1. SETS conceptual framework as presented in McPhearson et al. [36], McPhearson et al. [5], and Markolf et al. [21]. Besides inter-domain interactions, also referred to as "couplings", intra-domain interactions (e.g. socio-economic domain components interacting with each other) may occur and be considered in analytical approaches.

approaches cannot be used to explicitly represent nor study the interconnected structure and behavior of SETS. Furthermore, these analyses tend to overlook information available only at a qualitative level, which may still provide extremely valuable and diverse information for climate change adaptation [41–45]. Recent applications tackling SETS as complex, interconnected systems include the development of a causal-loop diagram (CLD) based on a literature and press review subsequently expanded through interviews with local stakeholders [31]. This study focused on understanding the interdependencies of a SETS by analyzing cascading ecological and technological processes leading to social impacts. However, social impacts were ultimately framed as a result of cascading infrastructural failures, yet they were not directly included in the network represented in the CLD, failing to represent couplings with the social domain (e.g. financial aspects and maintenance of infrastructures).

An additional challenge inherent to tackling climate change adaptation through SETS lies in the diversity of knowledge required to fully grasp their complexity. SETS approaches to climate adaptation require interorganizational, collaborative governance approaches that facilitate collective learning [30]. However, collaborative approaches to urban SETS often lack mechanisms for evaluating the diversity of knowledge underpinning them, leaving critical gaps in understanding how different actors conceptualize and engage with SETS. For instance, the complex systems-mapping exercise presented in Helmrich et al. [31] focused on eliciting stakeholder knowledge to validate a pre-defined causal network, rather than reflecting on the potential myriad of different framings held by the decision-makers interviewed. By knowledge diversity, we refer to the varying ways in which different stakeholders and stakeholder groups may understand and define a problem related to risk mitigation for climate change adaptation. Under a SETS lens, knowledge diversity is defined as the heterogeneous understandings that individuals and groups may have about how the social, ecological, and technological domains interact with each other [15]. Given the complexity of SETS, capturing the multiple understandings of the system held by different stakeholders is critical to understand how decision-makers engage and interact with the challenges at hand [15,46,47]. Understanding knowledge diversity in urban SETS for climate adaptation would provide insights into how different domains and couplings are unevenly understood or considered [46], consequently highlighting potential knowledge gaps and silos leading to an unbalanced understanding of certain parts of the system, and leading to adaptation decisions that fail to fully account for the interactions present in urban SETS. Recognizing knowledge diversity is thus crucial for identifying knowledge gaps, uncovering overlooked synergies, and informing inclusive decision-making processes. Developing such an understanding is especially crucial at the beginning of interdisciplinary adaptation planning processes, as it enables researchers and planners to bridge epistemological gaps, address stakeholder silos, and foster a more balanced understanding of urban systems [48,49]. Failing to acknowledge and facilitate knowledge diversity may exacerbate existing differences and tensions within collaborating teams, potentially leading to power imbalances and the maintenance of a status quo [50].

Few experimental approaches for understanding knowledge diversity in complex systems have been developed. However, the majority of these applications focus on environmental conservation through SES [15,49,51]. To the best of our knowledge, no methods for assessing knowledge diversity have yet been applied nor adapted to urban SETS for climate adaptation.

Building upon previous research on knowledge co-production for understanding complex systems and knowledge diversity analysis [52], we present a method for understanding knowledge diversity in urban climate change adaptation using a SETS lens. Here, we define knowledge co-production as "a collaborative process in which shared and useable knowledge is produced out of a pool of diverse knowledge sources and types" [12: p.46]. Knowledge co-production is considered a powerful approach for enabling collective learning through the exchange, production, and application of knowledge [53,54]. Collective learning through inter- and transdisciplinary processes is essential for climate change adaptation as it can support the integration of differing perceptions and needs [20,55–57].

This study holds two main objectives. First, we propose a novel methodology for mapping, visualizing, and analyzing urban systems by explicitly accounting for the interactions of their SETS components and domains. Second, we use this methodology to capture individual understandings of SETS and compare them in order to assess knowledge diversity related to climate change adaptation. We focus on the research question "How do experts involved in local urban adaptation to extreme weather events differently frame the social, ecological, and technological interactions of risk and adaptation?". Subsequently, we use the empirical findings to assess the capacity of our SETS-based approach to capture knowledge diversity, providing insights into the interdisciplinarity of the knowledge present in co-production for urban climate adaptation.

We rely on mental models to capture and compare individual perceptions of climate risk in an urban system. Mental models (also referred to as cognitive maps) are used to capture and represent the internal representations of reality, reasoning, and perceptions that characterize individual understandings and decision-making [49,58]. Here, we focus on the use of mental models for eliciting knowledge about complex systems, which are represented as complex webs of cause-and-effect associations [49]. Mental models allow us to engage with diverse knowledge and perspectives when tackling sustainability challenges [59,60]. We classify system components represented in each mental model using a SETS lens, to then analyze the system's characteristics in terms of relative prevalence of S, E and T domains both as nodes and as inter- and intra-domain interactions or couplings such as social-to-ecological (S-E), social-to-social (S-S) … etc. By capturing and analyzing individual framings of risk in urban systems, this approach identifies shared understandings, gaps, and tensions, providing a foundation for improved knowledge co-production and decision-making in climate adaptation. Thus, we contribute to operationalizing KS by empirically showcasing the value of evaluating knowledge diversity, providing insights that are critical for fostering inclusive and context-sensitive KS.

Taking adaptation to extreme precipitation in New York City (USA) as a case study, we showcase a SETS-based methodology that highlights how knowledge diversity leads to multiple framings of climate risk due to differing perceptions of the impacts of extreme weather events. While previous research has examined components of social, ecological, and technological systems in climate risk assessments, there remains a gap in understanding how these perspectives agree and/or differ within interdisciplinary teams. This approach identifies commonalities and gaps through the representations of SETS in mental models, providing a foundation for future knowledge co-production exercises that explicitly seek to bridge and integrate differing risk perceptions in order to enhance climate adaptation strategies.

In Section 2 we describe the case study area, highlighting NYC's experiences with recent extreme precipitation events and its wide risk governance context. In Section 3, we present the methods used to assess knowledge diversity by combining an FCM approach with a SETS lens. Section 4 presents the analytical results that stemmed in the case study. Section 5 discusses the implications of the study, considering the consequences of the empirical results obtained for the case study's context as well as the broader implications of the approach presented in supporting inter- and transdisciplinary approaches to climate change adaptation.

2. Case study area

New York City (NYC) is an especially relevant case study in climate adaptation, not only due to its physical vulnerabilities but also because of its pioneering approaches to integrating diverse knowledge and disciplines, fueled by its reliance on close science-policy collaborations.

With over 8.8 million inhabitants, NYC is the most populous city in the United States and has long endured extreme weather events such as heavy rainfall and heat waves throughout its modern history [61,62]. The city is located in the Northeast region of the United States, where some of the highest nation-wide increases in the frequency and intensity of extreme precipitation have been observed over the past century [63]. Further increases in extreme precipitation are projected in the coming decades [62,64,65]. Several extreme precipitation events have taken place over the recent years, including the succession of three named tropical cyclones (Elsa, Henri, Ida) that occurred during Summer 2021. Historic records for hourly precipitation were superseded twice in ten days, first during Hurricane Henri (August 21–22, 2021) [66,67] and then during the precipitation events linked to Ida's remnants (September 1–2, 2021) [68,69]. Flash flooding caused by Ida's remnants caused 56 deaths in the Northeast region, of which 13 died in NYC [70]. Additionally, Ida's precipitation caused severe property damages [68,71] and disruptions to the city's mass transit systems [72,73].

The city has its own advisory group of multi-disciplinary scientists, the New York City Panel on Climate Change (NPCC), established in 2009 [74]. Since NPCC's first report on the city's need to adapt its critical infrastructures to climate change, the NPCC has used a risk management approach to guide assessment [75,76]. In addition to the NPCC, the City's government recently established a group of city staff members from diverse municipal departments tasked with embedding scientific knowledge and climate data into their departmental policies [77]. This task force, named the Inter-agency Climate Assessment Team (ICAT), also plays a key role in identifying key knowledge gaps that steer the NPCC's research agenda. Since 2020, the city additionally leads the Climate Knowledge Exchange (CKE) initiative, an iterative engagement space through which city officials interact with scientists, federal institutions, and community organizations to identify NYC's research needs [78]. This complex landscape of interactions between NYC's government, researchers, and community organizations among others relies on the assumption that inclusive knowledge sharing would transform the way in which adaptation decisions are informed by local and scientific knowledge. However, a recent evaluation of the CKE initiative identified barriers to enhancing the inclusivity of knowledge co-production, such as a bias from institutions towards quantifiable data and the presence of inherent biases and practices related to political agendas and power structures [79]. As a result, the evaluation reported that certain issues aligning with existing agendas or capabilities might have been overrepresented.

Regarding extreme precipitation, NYC's adaptation efforts are considered exemplary by their focus on risk mitigation [7] and the approaches taken towards measuring, monitoring, and setting goals for long-term adaptation [80–82]. The city released its first green infrastructure plan for stormwater management in 2010, after assessing the economic advantages linked to integrating green and gray approaches for mitigating water quality compliance issues linked to combined sewer overflows [83]. While the plan successfully complements the performance of the city's under-dimensioned sewage systems, it does not address the impacts of extreme precipitation events [65]. Only in 2021, the city released its first-ever Stormwater Resiliency Plan (SRP) [84]. This plan included NYC's first-ever city-wide pluvial flooding hazard maps, developed thanks to technological advances and a significant investment in resources. Pluvial flood hazard maps have enabled spatially explicit risk and vulnerability assessments [65,85]. The latest NPCC report includes an in-depth analysis of the city's pluvial flood risk and adaptation options [65] developed in parallel to the city's Climate Vulnerability, Impact, Adaptation and Analysis Study (VIA), an initiative focused on assessing the socio-economic impacts of extreme weather events in the city [86]. The VIA study resulted in the development of the city's first-ever Flood Vulnerability Index, a census-tract level map identifying communities most vulnerable to coastal flooding. Due to a lack of empirical understanding of the impacts of extreme precipitation on NYC's communities, a pluvial flooding vulnerability index was not developed during the study and research is currently in its early stages.

NYC is thus an important location to examine a city's active efforts towards co-producing and integrating climate risk knowledge into climate adaptation planning, and serves as a critical case study for other cities to learn from. In a context where inter- and transdisciplinary collaboration is embraced as a common practice, identifying persistent knowledge gaps and common framings can illustrate how diverse perceptions are integrated into decision-making (or not), the barriers that hinder knowledge exchange, and how these dynamics shape the capacity of cities to address emerging climate risks. Additionally, we focus on extreme precipitation as a hazard that has only recently become a critical concern to the city, and about which knowledge may remain scattered compared to other hazards with a longer history of adaptation planning in the city (e.g. heatwaves and coastal flooding).

3. Methods

Fuzzy cognitive mapping (FCM) has emerged as a powerful tool in urban and climate adaptation contexts, providing insights into diverse knowledge framings and fostering inter- and transdisciplinary approaches to complex challenges [12,43,49,87,88]. We use FCM in this study to elicit mental models from different stake- and knowledge holders. FCM is a 'soft-systems' approach valued for its capacity to capture mental modes as complex webs of cause-and-effect associations [48,89]. As such, FCM is capable of representing individual assumptions, knowledge, beliefs and experience in an organized and comparable manner [90]. It allows for the inclusion of soft variables that may be hard to quantify due to data scarcity or their qualitative nature [43].

Representing complex systems as cause-effect networks in FCM resembles other qualitative complex systems mapping methods such as Causal Loop Diagrams (CLD). However, fundamental differences between CLD and FCM led us to choose FCM as the primary methodology for this study. While CLD is often used to understand the system's dynamics and identify feedback loops, FCM is particularly focused on capturing, visualizing, and analyzing the differences in the perspectives (cognitions) of participants [91,92]. This feature is further exemplified in the use of weights to grade the strength of relationships drawn by participants, reflecting their perception of the influence of specific elements on the system.

We follow the stepwise approach to FCM developed by Olazabal et al. [12,93] based on Özesmi and Özesmi [94]. Specifically, we replicate steps 1 to 4 in our study (Table 1). This study's focus on understanding knowledge diversity through a SETS lens does not require the aggregation of individual perspectives into a unique meta-model (step 5).

Step 1 Problem Definition

Step 1 focuses on defining the objective and scope of the study. As stated above, the study's goals were to understand the diverse ways in which the impacts of extreme weather events are perceived by local stakeholders directly involved in urban adaptation to climate change. A SETS approach was selected to identify knowledge diversity by assessing how SET domains and couplings are differently perceived by participants.

Step 2 Knowledge Elicitation

Step 2 develops the elicitation of participants' knowledge, including the identification of participants, designing the interview's FCM mapping process, and carrying out the FCM mapping exercises. The target participants of this approach were local experts actively involved in the production and use of risk knowledge for climate adaptation planning [12]. We aimed to recruit participants across a diversity of sectors (e.g. health, urban planning, green infrastructures …) to optimize the interdisciplinarity of the sample as well as to balance the representation of social, ecological, and technological knowledge domains. We focused our selection on researchers who had recently carried out context-specific pluvial flood hazard modeling, analysis, and risk assessment studies. Researchers closely interacting with local policy makers (e.g. through research partnerships) were prioritized given the study's focus on supporting inter- and transdisciplinary co-production processes. Additionally, we selected local decision-makers involved in integrating climate risk knowledge into decision-making processes, as well as those involved in responding to the short and long-term impacts of extreme weather events on the city's services and infrastructure. In addition to pre-selected academic experts and decision-makers, we used a snowball sampling approach, asking interviewees to recommend other participants whose knowledge they considered valuable for the study.

In the study's case study, the selection criteria for identifying participants translated into contacting researchers contributing to the NPCC4, the VIA project, and others. Regarding local government's decision-makers, we primarily selected NYC policy makers belonging to or closely interacting with ICAT, given their involvement in sharing and integrating climate risk knowledge in their office's specific activities, as well as in informing and steering climate risk research based on the priorities and needs identified at the governance level. We contacted decision-makers from other NYC offices not present in ICAT in order to increase the different perspectives elicited from diverse city managers. Besides directly contacting individuals with requests for an interview, additional researchers and decision-makers were recruited at the participatory research workshop "Adapting to Multiple and Cascading Climate Change Hazards and Risks" organized by the Civic-Led Urban Adaptation Research Center, held in February of 2024 [95].

Knowledge elicitation in FCM applications varies based on the analytical goals. Processes focused on building consensus through negotiation and integration of perspectives rely on participatory FCM processes that involve group workshops [96]. Here, our focus on leveraging knowledge diversity calls for using individual interviews through which participants are encouraged to express their

Table 1
Steps and intermediate processes undertaken in this study. Adapted from Olazabal et al. (2018b).

Step	Intermediate Processes
1. Problem Definition	Definition of the study's objective
	Definition of the study's scope
2. Knowledge Elicitation	Identification of relevant participants
	Interview design
	Individual interview-based fuzzy cognitive mapping exercises
3. Data Treatment	Digitize hand-drawn mental models in Miro and Mental Modeler
	Share Miro version of model with participant for reference
	Coding maps into adjacency matrices
	Coding nodes as Social, Ecological, or Technological
4. Homogenization	Selection of common terminology + scale
	Renaming concepts
	Reversal of weight signs
	Computing Jaccard Similarity Coefficient (JSC)

individual views without having to work towards a consensus (see Supplementary Materials 1 for interview protocol). Knowledge diversity was also enabled by designing the interview process using open questions instead of providing participants with pre-identified concepts [12,43]. The mapping exercise was structured into three main questions used to guide the development of a cause-effect network on an A1-sized piece of paper. In the first question, the interviewee was asked to list and connect the impacts of a specific extreme weather event (in this case, extreme precipitation in NYC) in a cause-effect network. Second, the interviewee was asked about potential drivers, pressures, and system characteristics that may influence the impacts identified previously. This question was added in order to capture critical contextual information that may be lost when limiting questions to the impacts of extreme precipitation. In the final question, the participant was requested to add potential responses and interventions that would be useful to mitigate the impacts of extreme precipitation in the drawn system. Finally, participants weighted each relationship represented in the cause-effect network based on the strength of the influence. Participants were requested to weigh each relationship qualitatively with a sign (negative or positive) to indicate an increasing or decreasing effect - and on a binary scale (weak or strong) to express the strength of the relationship. This binary weighting was selected in order to minimize the cognitive burden caused by the process of weighting dozens of cause-effect relationships at the end of the interview [97].

Step 3 Data Treatment

Step 3 relates to the post-processing of individual FCMs. Elicited maps were digitized as graphs in a Miro Board (https://miro.com/). Digitized maps were shared with each individual participant for their feedback, requesting clarifications if needed. Maps were also digitized using mental modeler, a mental models analysis tool [98]. Following Olazabal et al. [12,93], we collected the nodes of each individual map into a workbench (Supplementary Materials 2) to facilitate a transparent and reproducible post-processing of the elicited variables. In the post-processing, each node was classified as either Social, Ecological, or Technological depending on the SET domain being referred to. This classification was done based on the overview of SET components and interactions developed in Markolf et al. [21]. A notable aspect of this classification is that rules, codes, and regulations are classified as social regardless of the domain impacted. Coding nodes as S, E, or T allows analyzing how the different SET domains and couplings are represented in each map. To better represent this, each individual map was condensed into a "SETS coupling diagram" with just three nodes (S, E, T). SETS coupling diagrams graphically represent the total number of nodes belonging to each domain, as well as the total number of couplings, including both inter-domain relationships (e.g. social-to-technological relationships) and intra-domain (e.g. social-to-social). To enable a quantitative comparison, each FCM was summarized based on the percentage of nodes classified in either domain, as well as based on the percentage of its SET couplings.

Step 4 Homogenization

Step 4 focuses on homogenizing individual interviews to a common set of variables. In this study, we homogenized the coded SET nodes to a common terminology in order to compute the Jaccard Similarity Coefficient (JSC) to quantify the overlap between maps. It is obtained by dividing the intersection size by the union size of two samples (Equation (1)). JSC can be used to assess the similarity between either the nodes or the relationships shared across two FCMs, as a proxy for agreement between two individuals or groups in their perceptions of a system's component (nodes) and structure (relationships) [12,15,94]. In order to ensure transparency and reproducibility, the entire homogenization process was carried out by the same analyst who had conducted, digitized, and analyzed the interviews in order to avoid losing important connotations and interpretations implicit in the nodes, as recommended by Olazabal et al. [93]. Homogenized variables are additionally provided in the workbench supplied in Supplementary Materials 2.

$$JSC\ (G_1, G_2) = \frac{N_1 \cap N_2}{N_1 \cup N_2} \qquad \text{Equation 1)}$$

Where G_1 and G_2 are two graphs, and N_1 and N_2 are the set of nodes in each of them. To compute the JSC of relationships instead of the nodes, N_1 and N_2 would be replaced by each graph's set of relationships between pairs of nodes.

During the homogenization process, some nodes were aggregated or disaggregated in order to maintain consistency of terms and scale, as presented in Olazabal et al. [12,93]. Aggregated and disaggregated terms were color-coded in the workbench.

4. Results

4.1. Summarizing elicited knowledge through a "SETS couplings diagram"

A total of 36 people were contacted and invited to participate in an FCM mapping exercise, from which 20 (55.6 %) were successfully interviewed. Interviewed participants equally represented researchers (n = 10) and city-government decision-makers (n = 10).

Participants also represented diverse sectors or areas: green and blue infrastructures (n = 6), infrastructure and urban planning (5), socio-economics (5), health (2), emergency management (1), and climate change (1). This classification into sectors, however, is a general estimation based on participants' primary institutional affiliations and roles, recognizing that many participants may contribute to multiple areas within their professional capacities.

The representation of SETS across the elicited mental models varied significantly. A total of 639 concepts or nodes were elicited across the 20 interviews, from which 291 (45.5 %) were classified as social, 150 (23.5 %) as ecological, and 198 (31.0 %) as technological. Interviews also showed variable complexity and structure, with an average of 32.0±8.3 nodes per model, and 49.4±17.1 relationships.

Combining the components of each mental model into a SETS coupling diagram highlights that each interviewee perceives the challenge of extreme precipitation in NYC differently, emphasizing different specific domains and interactions (Fig. 2). Several combined SET models lack one or more SET couplings (interactions between variables from different domains), indicating a partial representation of the SETS in the individual mental models. Of the 20 FCMs developed, only 4 of them represented every possible SET coupling.

Zooming into each participant's cognition of extreme precipitation in NYC as a SETS coupling diagram provides further insight into how they problematize the need for climate adaptation. For instance, participant 13 (Fig. 3), a social scientist, considered the impacts of extreme precipitation in NYC as mainly social, with strong technological-to-social interactions. In addition, adaptation solutions were mostly framed as causally responding directly to climate impacts. Participant 2, an advisor to NYC's stormwater management agency, considers the performance of infrastructure to cascade into social impacts as well as to be heavily influenced by ecological processes (Fig. 4). While the model represents a large amount of technological-to-technological interactions, intra-domain relationships are absent in the social and ecological domains. In interview 16, a landscape ecology researcher focused on the underlying ecological processes that lead to the increased impacts and hazards of extreme precipitation (Fig. 5).

Characterizing each mental model based on the representation of the SET domains enables the identification of common framings and knowledge gaps. As shown in Fig. 6, the elicited mental models predominantly frame the impacts, drivers, and responses against extreme precipitation in NYC as a socio-technological challenge with minor representation of the ecological domain. This pattern is in line with the overall abundance of social and technological nodes across the interviews, in contrast to the lower number of ecological nodes. Participants whose mental model has more than 33 % of the total nodes classified as ecological are specialized in the ecological domain (e.g. landscape ecologists, climate scientists, and decision-makers in NYC's Parks Department). Additionally, areas devoid of respondents can be identified in the plot, hinting at potential knowledge gaps in the interview sample.

The distribution of inter- and intra-domain couplings further highlights the knowledge diversity and potential gaps of the elicited mental models. Intra-domain relationships (social-to-social, technological-to-technological, and ecological-to-ecological) are most common on average (Fig. 7). Inter-domain relationships are less common than intra domain relationships, with technological-to-social relationships being the only exception.

4.2. Homogenized mental models: similarity analysis

After carrying out the homogenization of concepts across individual interviews, the total number of nodes was reduced from 639 to 248. For example, various types of small-scale, street-placed green infrastructure interventions (e.g. bioswales, rain gardens, constructed wetlands … etc.) were homogenized to the node "green infrastructure for stormwater management". In some cases, variables ambiguously defined by participants were broken down into several nodes. For instance, participant 24 lumped flooding of diverse transportation infrastructures as a single variable (subway flooding, railroad flooding, and general disruptions to mobility systems). This single variable was broken down into three separate nodes given that other participants focused independently on one or more of them, generating pathways applicable exclusively to either one (i.e. disruptions to mobility systems being caused by other impacts than direct flooding). 50.8 % (n = 126) of the homogenized concepts corresponded to the social domain, whereas 24.6 % corresponded to ecological and technological (n = 61 for both domains). The percentage reduction was similar for the social and ecological domains, whose sample size was reduced 57 % and 59 %, respectively. Nodes in the technological domain experienced a higher reduction rate (69 %), meaning that the original information was reduced to a relatively lower number of variables.

The JSC values obtained from pairwise comparisons across the interviews illustrate a high degree of variability in the concepts considered in individual mental models. JSC values across pairwise comparisons of the homogenized maps averaged 12.7 % ± 6 %. When comparing JSC values per domain, we observe that social variables were the most diverse (highest number of unique nodes, with lowest repetition across interviews), while technological variables showed the greatest degree of overlap across interviews. (Fig. 8).

Recurrence of relationships across homogenized maps was extremely low (Supplementary Materials 5). Only 134 (16.5 %) of the total homogenized relationships occur in more than a single mental model, and only 12 (1.5 %) occur in more than 5 interviews. Remarkably, however, the most repeated relationships across the mental models tend to represent couplings between different domains (Table 2), especially technological-to-social.

5. Discussion

Complex and interdependent components of urban systems call for interdisciplinary approaches to climate change adaptation. However, difficulties remain in how to integrate multiple ways of knowing despite wide agreement that doing so would improve both research and practice. Such difficulties stem from the fact that besides systems being complex, the goals, values, and perceptions linked to them vary [99]. To enable transformative and sustainable pathways, urban SETS must be managed as fully coupled in order to minimize negative trade-offs [5]. Consequently, adaptation planning efforts aiming to integrate the multiple domains of complex urban systems must begin with recognizing the need for linking, integrating, and making sense of diverse sources of knowledge. Thus, understanding knowledge diversity throughout knowledge co-production processes is critical.

As a step towards addressing this challenge, this study's goal was to assess the diversity of knowledge among experts involved in climate adaptation planning, using adaptation to extreme precipitation in NYC as a case study. Applying a SETS lens enabled the

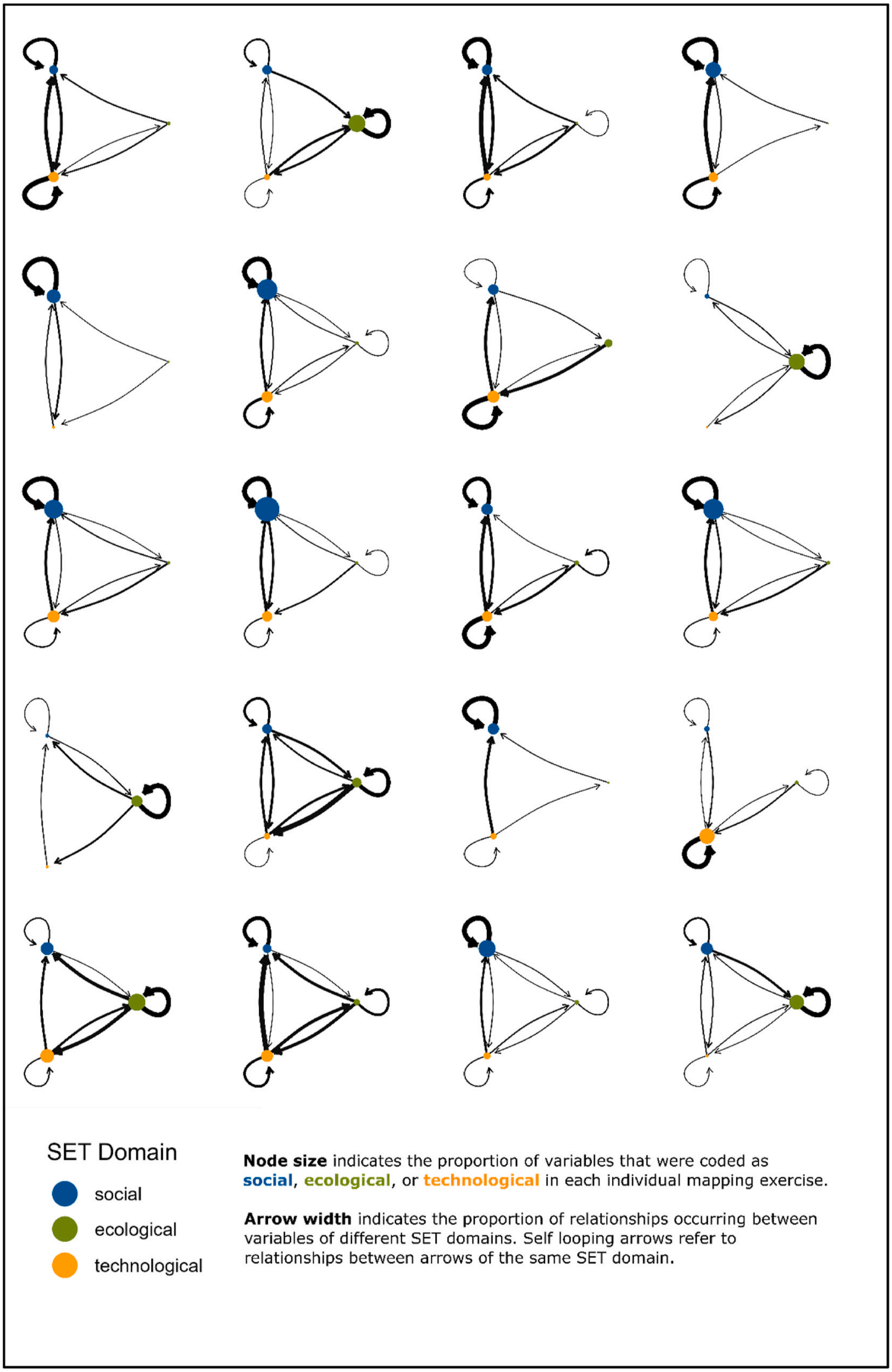

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Fig. 2. Combined SETS couplings for each of the 20 mental models developed through interviews. The mental models accounting for all the possible uni-directional couplings are shown in the bottom row.

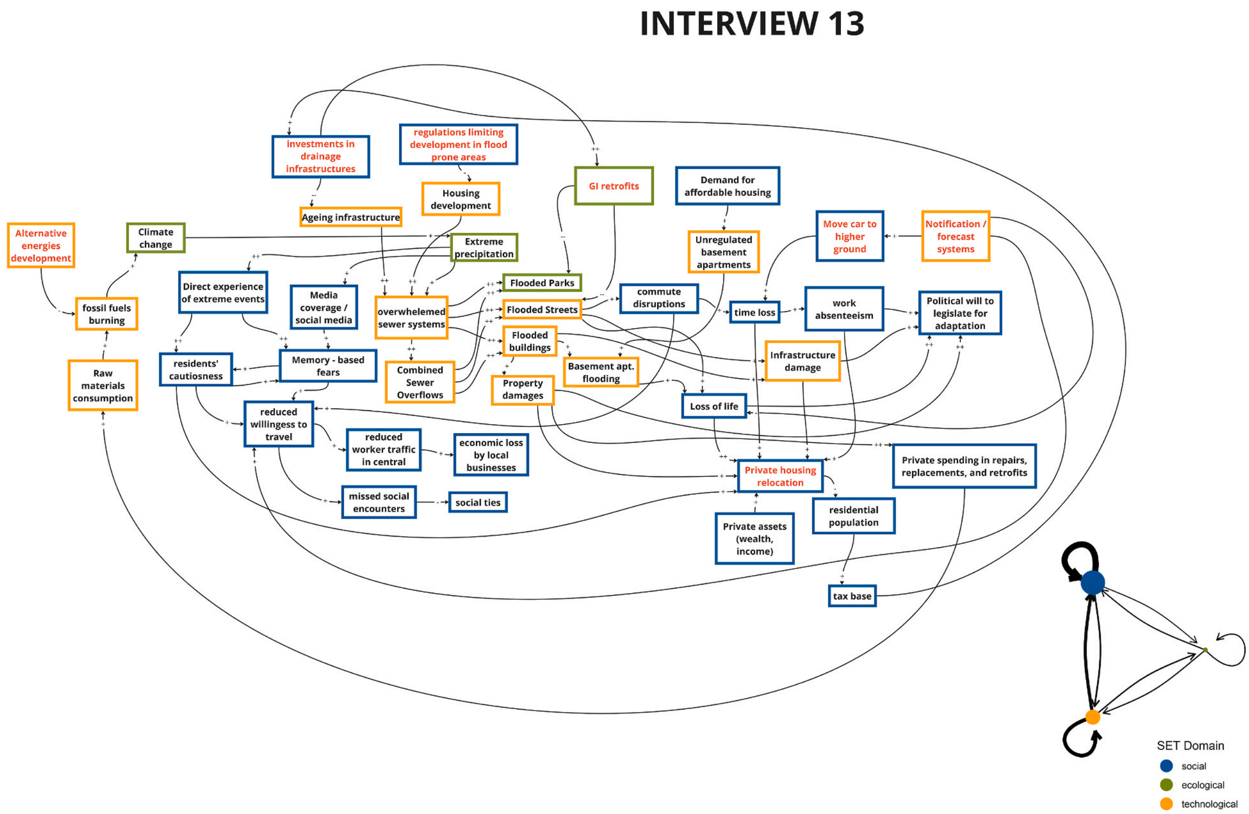

Fig. 3. Participant 13's individual mental model. The color of each component represents the SET domain to which the component was assigned.

identification of distinct framings of extreme precipitation risks and responses, as well as potential knowledge gaps. Only a minority of the elicited mental models (4 out of 20) accounted for every possible SET coupling, reinforcing the need for inter- and transdisciplinary approaches to tackle the complexity of urban climate adaptation by integrating diverse perspectives [100].

5.1. Understanding knowledge diversity, gaps, and narratives through SETS-based FCM

Differences across individual mental models illustrate how disciplinary backgrounds shape the framing of extreme precipitation adaptation in NYC. For example, participant 13's closed-loop framing suggested adaptation to be driven by the intensity of previously experienced impacts, aligning with previous findings on risk perception and policy response dynamics [101]. While generalized, this hazard-centric approach to urban adaptation may obscure socio-political processes of risk creation [102]. Participant 2's emphasis on cascading infrastructural failures relates to systemic perspectives on infrastructure interdependencies in urban flooding [30,31,103, 104]. Finally, participant 16's mental model suggests a circular interaction where socio-economic drivers shape urban development and infrastructure, which in turn alters ecological processes, ultimately affecting society.

The observed prevalence of social and technological nodes in individual mental models, except for those elicited from experts in the ecological domain, points to a potential isolation of ecological knowledge within specialized practitioners and researchers. While ecological nodes were generally underrepresented across the individual interviews, the most commonly mentioned adaptation response was an ecological one (green infrastructure for stormwater management). This suggests that ecological considerations are not absent from expert thinking, but rather integrated as actionable strategies within a broader socio-technological adaptation paradigm. Additionally, the results point towards potential missing knowledge on the links between social and ecological as well as ecological and technological interactions resulting from extreme precipitation impacts in NYC. These findings align with the NPCC's latest report [65], which calls for further research on the interactions between flooding and the city's natural and nature-based systems (NNBS). Beyond the specificities of the case study, recent scholarship has called for expanding the understanding of the resilience of urban NNBS [105].

Regarding the prevalence of intra-domain over inter-domain couplings, the empirical approach taken in this study illustrates how KS and institutional structures tend to operate within single domains and struggle to make sense of complexity in SETS [30]. While

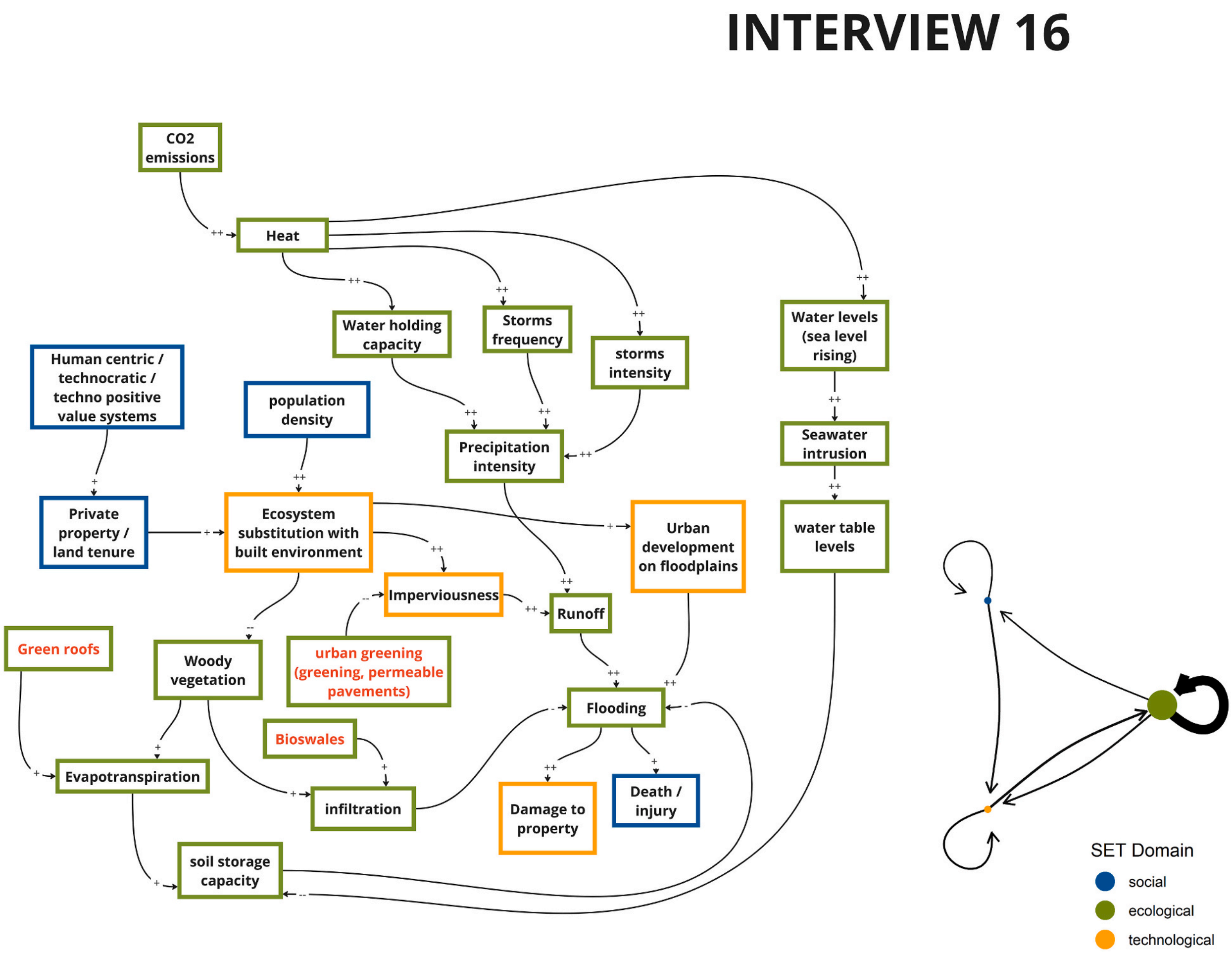

Fig. 4. Participant 16's individual mental model. The color of each component represents the SET domain to which the component was assigned.

knowledge integration approaches may handle the fact that no single stakeholder can hold the totality of a complex system's knowledge [12], collaborative, cross-disciplinary, and participatory approaches to transforming KS are critically needed to enable stakeholders involved in climate adaptation to account for the interactions between different sectors and domains [106].

The lower similarity for nodes classified as social may be explained by the significantly higher number of different concepts assigned to the domain, even post-homogenization. Integrated assessments tend to further subdivide the social domain. For instance, Grabowski et al. [107] approached infrastructures as socio-eco-technical systems using a PFEST framework considering political, financial, and social factors in addition to ecological and technological. Fonseca et al. [108] rely on a PESTEL approach that combines political, economic, social, technological, environmental, and legal dimensions for exploring nature-based solutions. Future SETS-based assessments may need to account for potential case-specific subdomains, as originally presented by Markolf et al. [21]. For instance, digital systems (e.g. emergency alerts and notifications) are increasingly becoming a key component of the technological domains of cities, in addition to the more traditionally assumed hard infrastructure systems (e.g. roads, buildings).

In line with Olazabal et al. [12]'s findings, the overlap in specific connections across individual mental models was extremely low, even in cases when two mental models showed high co-occurrence of concepts. The majority of the most repeated relationships were classified as technological-to-social couplings. While inter-domain relationships are less common than intra-domain across the mental models, specific inter-domain relationships tend to be most commonly repeated. A high representation of specific technological-to-social relationships may be capturing the common conception of flooding as a result of infrastructural failures and cascading physical impacts [21,103,104]. More broadly, these perceptions may perpetuate technocratic perceptions that frame climate adaptation as an infrastructural fix, and which have been identified as barriers to sustainable, just, and effective adaptation [109,110]. The consensus represented in the high similarity of technological-to-social interactions over other types of couplings further reinforces the need for focusing future knowledge co-production on the interactions across other domains. As NYC explores both soft and hard interventions to mitigate the impacts of extreme precipitation and other types of extreme weather events [65], focusing on co-producing socio-ecological and ecological-technological knowledge would balance the representation of inter-domain couplings that inform adaptation decisions.

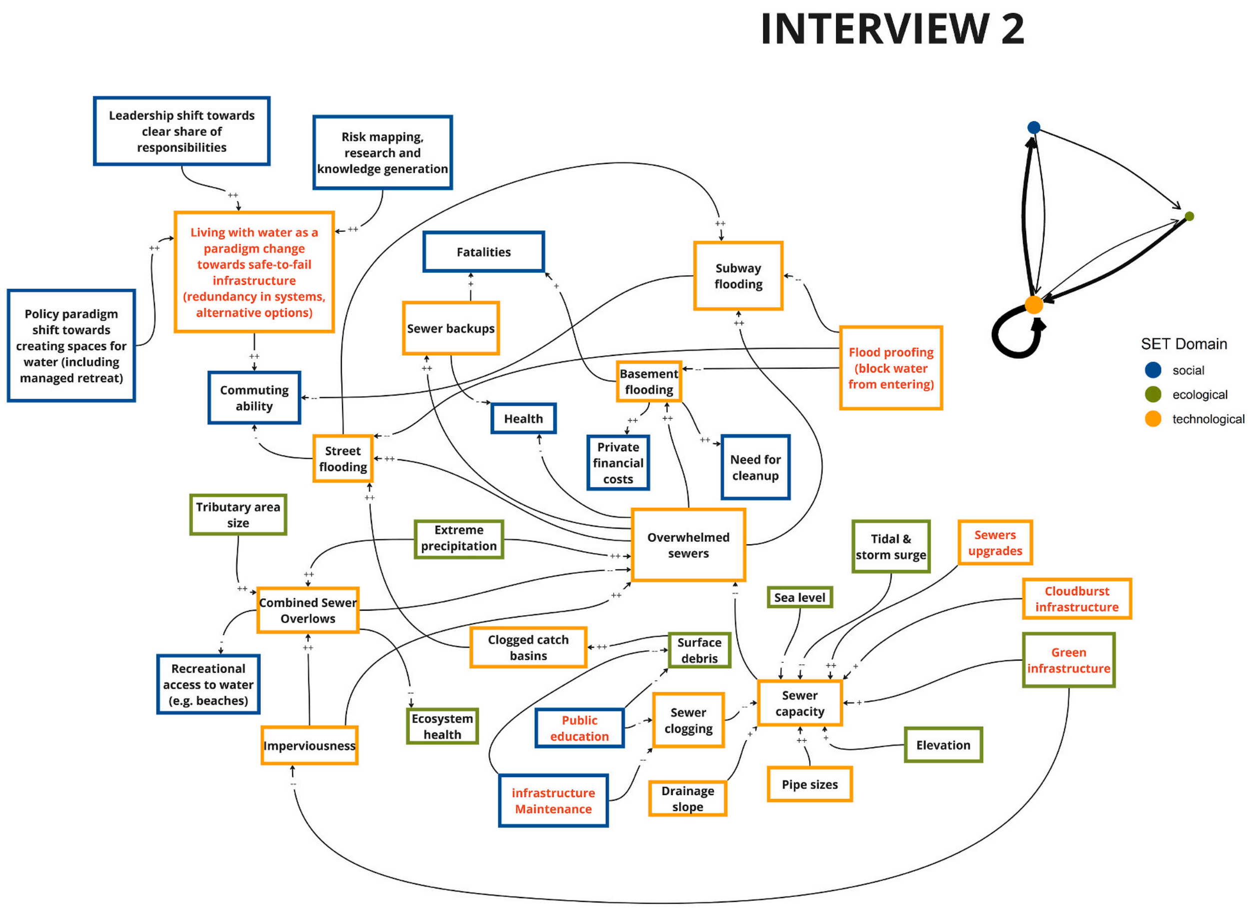

Fig. 5. Participant 2's individual mental model. The color of each component represents the SET domain to which the component was assigned.

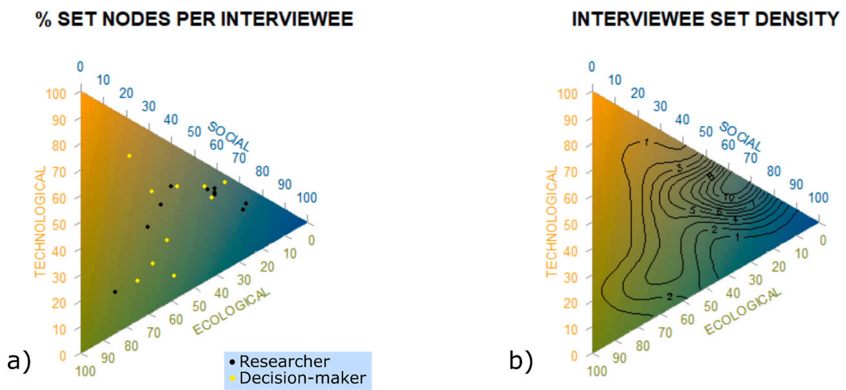

Fig. 6. Predominant SET framings of extreme precipitation in NYC. Ternary plots depicting (a) Percentage distributions of S, E, and T components in the 20 interviews carried out. Each dot represents an individual interview, which is placed based on the prevalence of S, E, and T nodes. Void areas (areas without points) indicate potential knowledge gaps due to the absence of mental models with SET distributions fitting them. Figure (b) presents the interpolated interview density, where higher values indicate a higher expected number of stakeholders.

5.2. Implications for climate adaptation and knowledge Co-production

As shown in the presented case study, combining mental models with a SETS lens holds promising value to enable inclusive interdisciplinary approaches to climate adaptation. Mental models elicited through FCM allow for capturing a participant's experience, knowledge, and perceptions about a system [12,87]. By focusing on individual-level analysis, this study builds on and extends

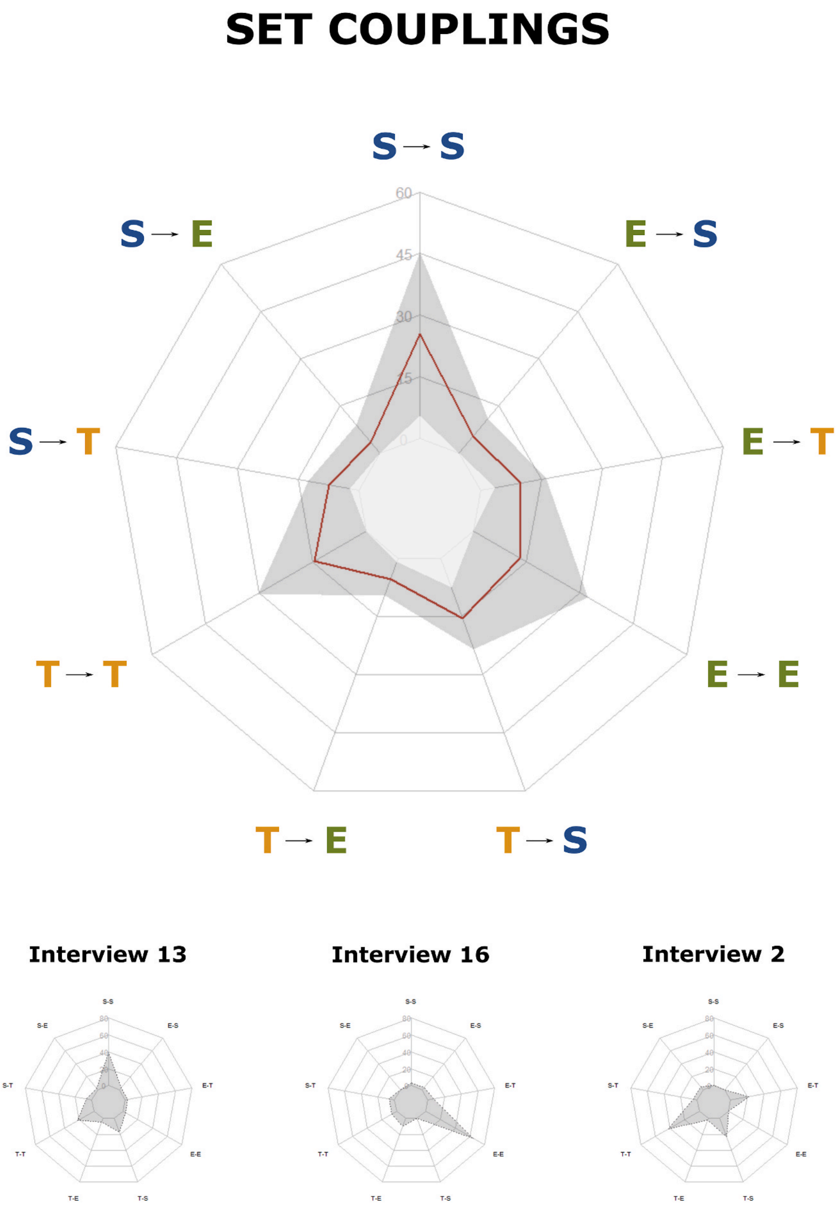

Fig. 7. Summary distribution of each of the possible SET couplings (relationships) across the 20 interviews developed. In red, the average percentage each coupling represents in the elicited mental models. In gray, the standard deviation band. Individual charts for participants 13, 16, and 2 illustrate variability in couplings at an individual level. Individual SET coupling diagrams are provided in Supplementary Materials 3.

previous work that aggregated stakeholder perceptions in SES [15,49]. In this study, we illustrate how using a SETS lens for analyzing climate risk perceptions provides a practical and interpretable reduction of the complexity inherent to mental models, serving as a first knowledge diversity screening mechanism. The novel combination of mental models and SETS addressed the need for tackling urban challenges holistically, transcending limitations of SES and STS-based frameworks that inherently miss interdependencies critical to urban environments [5,21,34,35].

The presented methodology not only contributes to assessing knowledge diversity but also aligns with key KS principles by identifying epistemological gaps that may hinder knowledge co-production. For instance, the observed isolation of ecological knowledge among specialized stakeholders and the prevalence of technological-to-social interactions highlight areas where governance processes might need to prioritize interdisciplinary collaboration and knowledge integration. By explicitly linking individual-level knowledge diversity to broader institutional dynamics, this study provides actionable insights into how co-production efforts can bridge disciplinary and epistemological divides in urban adaptation. The persistent gaps and framings we identified in a city known for its climate knowledge exchange approaches highlight that even when knowledge is co-produced, knowledge diversity can reveal insights into the dominant narratives shaping climate adaptation planning.

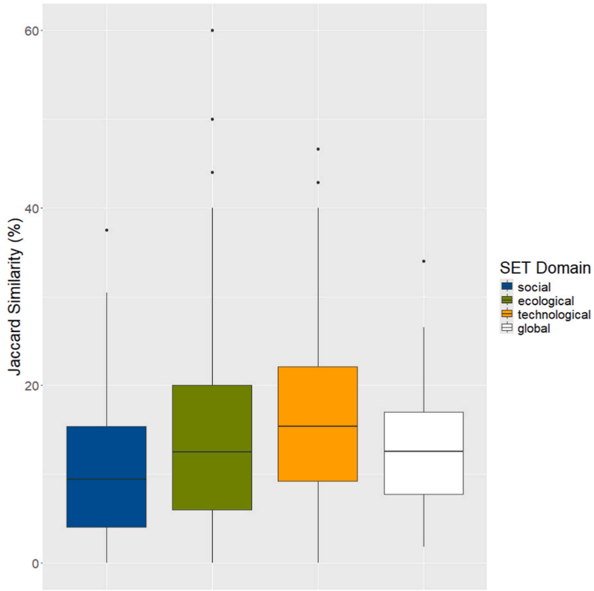

Fig. 8. Jaccard similarity coefficients across interviews based on components for global, S, E, and T. Readers may refer to Supplementary Materials 4 for cross-interview JSC index matrices.

Table 2
Most abundant relationships (causal connections between specific nodes) across the individual homogenized mental models (out of a possible 20).

From	To	Count
Residential Flooding (Incl. Basements) (T)	Fatalities (S)	10
Mold (E)	Public Health (S)	7
Physical Damages To Private Property (T)	Private Economic Losses (S)	7
Disrupted Mobility Systems (T)	Personal Mobility (S)	6
Physical Damages To Private Property (T)	Psychological Impacts (S)	6
Residential Flooding (Incl. Basements) (T)	Physical Damages To Private Property (T)	6
Street Flooding (T)	Personal Mobility (S)	6
Extreme Precipitation (E)	Street Flooding (T)	5
Green Infrastructure For Stormwater Management (E)	Imperviousness (T)	5
Housing Affordability (S)	Unregulated Basement Apartments (T)	5
Notification And Forecast Systems (T)	Fatalities (S)	5
Unregulated Basement Apartments (T)	Residential Flooding (Incl. Basements) (T)	5

Cities aiming to tackle climate adaptation planning through collaborative, inter- and transdisciplinary approaches may benefit from the presented methodology. Throughout the interviews, the vast majority of participants informally expressed optimism and excitement about the potential benefits of systematically collecting, comparing, and integrating diverse perspectives related to extreme precipitation. Besides the ultimate goals of the process, participants appreciated taking the time to develop and reflect about their own mental models, and several of them requested capturing their original drawn model with a photograph. Two pairs of participants belonging to the same institution were interviewed, and both pairs expressed their interest in contrasting their own mental model with that of their peers. This experience shows how useful it is, both individually and collectively, to reflect on one's own mental perceptions and how richer and more diverse knowledge can be gained through the experience of participating in co-creation exercises. Beyond advancing scientific understanding, these tools can enhance communication among stakeholders, support interdepartmental collaboration, and inform inclusive policy development. While the application of these methods to policymaking remains a challenge due to institutional constraints and time-consuming engagement requirements, their value in awareness-raising and capacity-building initiatives is evident.

5.3. Limitations and future avenues in mapping SETS knowledge

We identify several potential avenues for refining and tackling the limitations of the approach showcased in this study. A key limitation relates to the classification of variables into social, ecological, and technological categories, which, despite being guided by established SETS principles, may become challenging, and involves a degree of research subjectivity [21]. Our approach towards component classification aligns with established protocols for systems and FCM research [12,31,51,93]. We propose two combinable avenues for enriching the process of classifying variables. First, the classification of elements may be carried out in a participatory setting with the participants of the process. Second, a fuzzy sets theory-based approach may be used to allow for multi-membership classifications of SET components [111]. The combination of these two approaches may provide deeper insights into the diversity of knowledge among participants of co-production processes, recognizing that multiple epistemologies may define elements differently due to a lack of a shared language [112]. This avenue, however, requires a considerable increment in engagement, and has so far only been experimentally tested with scholars [111]. Thus, transdisciplinary applications involving decision-makers or other non-academic actors should assess the trade-offs of carrying out such a process given the limited availability of their participants.

Another challenge emerged in the cognitive burden associated with assigning weights to relationships within the mental models. Despite the use of simplified qualitative distinctions, many interviewees expressed difficulty in specifying the strength of relationships due to uncertainty in the underlying causal mechanisms. Addressing this issue may require alternative elicitation techniques that reduce decision fatigue while capturing the nuances of participants' reasoning, such as structured pairwise comparisons to help participants systematically assess relationships, confidence-based weighting that allows interviewees to express uncertainty alongside their estimates, or participatory group discussions where stakeholders collaboratively assign and debate weight values, reducing individual cognitive load.

The results presented in this study illustrate knowledge diversity and knowledge gaps in a sample of local experts involved in climate change adaptation in NYC. The results of this experimental analysis are representative of the sample consulted (i.e. the 20 individuals). Given their central role in adaptation planning in NYC, we consider them a solid first iteration of a process that may be expanded by adding a wider diversity of stakeholders at the same level. For instance, stakeholders directly involved in housing and zoning may provide key insights related to the pathways through which housing shortages interact with pluvial flooding. Beyond increasing the interdisciplinary nature of the sample, additional ways of knowing are yet to be incorporated through a wider engagement that exceeds the scope of this explorative analysis. For instance, accounting for alternative and informal types of knowledge (e.g. community knowledge and dynamics linked to everyday decision-making contexts) may illustrate parts of the SETS in which there is more or less alignment between civic groups and stakeholders with decision-making capacity. We acknowledge that these other ways of knowing are valid and hold significant potential to enrich knowledge co-production processes [106]. Ongoing calls for breaking epistemological injustices call for including actors lacking influence, as well as views that are alternative to dominating perceptions [113]. While civic organizations were included in the initial sampling process, the response rate was too low to generate a sample size comparable to the samples obtained from researchers and policy makers - one single civic organization responded and agreed to carry out an interview. Given that this lower response by civic organizations may relate to time and resource constraints, future iterations of this approach should consider targeted engagement strategies so that knowledge diversity accounts for alternative and confronting views present in community knowledge.

This study's main goal is to provide methods to support interdisciplinary adaptation planning processes by centering the attention on knowledge diversity to identify knowledge gaps and common framings. Hence, presenting the final results to participants and stakeholders involved in climate adaptation is a key next step to add to the analytical approach presented. Furthermore, we anticipate further developing this process in line with other systems-based approaches that focus on understanding and transforming the system itself, rather than on contextualizing the multiple and complementary perceptions of the system itself [31,45,48,94,114]. As part of this added engagement, a meta-model integrating individual mental models may be co-developed to then deepen the understanding of the system, through scenario analysis and graph-theory-based network analysis [12]. While these extensions would deepen insights into urban adaptation challenges, the current findings already provide a valuable foundation for understanding knowledge diversity and its role in climate adaptation.

6. Conclusions

Addressing knowledge diversity is crucial for tackling the interconnected impacts of extreme weather events in complex urban environments. Framing cities as Social-Ecological-Technological Systems (SETS) enables holistic approaches to urban climate adaptation, but this complexity requires identifying how different stakeholders perceive and engage with system components. This study underscores the value of combining mental models with a SETS lens to identify knowledge gaps and enhance system understanding for more effective adaptation strategies.

The SETS diagrams illustrate key insights regarding stakeholder perceptions of the role played by S, E, and T domains in the impacts caused by extreme precipitation in NYC. In the context of the presented case study, this methodology allowed for i) identifying missing SETS combinations hinting at potential knowledge gaps, ii) identifying a low percentage of inter-domain interactions, pointing at potential knowledge silos hampering the understanding of NYC as an interdependent system, iii) ecological knowledge being at risk of isolation by being present mainly in the mental models of specialized stakeholders, and iv) identifying specific technological-to-social relationships as the most repeated. Based on the results, future knowledge co-production in NYC should address these gaps by prioritizing the integration of the ecological domain beyond specialized knowledge holders, as well as fostering a balanced understanding of inter-domain interactions beyond the influence of infrastructure systems on society.

Beyond NYC's case study, this methodology underscores the critical need for integrating diverse perspectives and disciplines when tackling urban climate adaptation and risk governance processes. We offer a practical foundation for strengthening the dynamics of KS by identifying knowledge gaps, fostering inclusive co-production processes, and supporting more holistic and equitable governance frameworks. We have shown how knowledge co-production processes inserted in modelling and knowledge systematization efforts, must explicitly reflect on the diversity of knowledge available in order to identify potential knowledge gaps, synergies and opportunities for a more holistic and integrative approach to climate adaptation in urban environments. The approach we present in this paper constitutes an important theoretical and empirical foundation for future advanced risk assessment efforts that aim to tackle the multifaceted challenges of complex urban systems.

CRediT authorship contribution statement

Pablo Herreros-Cantis: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Svetlana Khromova:** Writing – review & editing, Conceptualization. **Marta Olazabal:** Writing – review & editing, Conceptualization. **Timon McPhearson:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Johannes Langemeyer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Marc B. Neumann:** Writing – review & editing, Supervision, Methodology, Funding acquisition, 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2025.105550.

Data availability

Data will be made available on request.

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