Systems Research and Behavioral Science
Syst. Res (2018)
Published online in Wiley Online Library
(wileyonlinelibrary.com) **DOI**: 10.1002/sres.2519

■ *Research Paper*

Transparency and Reproducibility in Participatory Systems Modelling: the Case of Fuzzy Cognitive Mapping

Marta Olazabal[1*], Marc B. Neumann[1,2], Sébastien Foudi[1] and Aline Chiabai[1]

[1] *Basque Centre for Climate Change (BC3), Leioa, Spain*
[2] *IKERBASQUE, Basque Foundation for Science, Bilbao, Spain*

By aggregating semi-quantitative mind maps from multiple agents, fuzzy cognitive mapping (FCM) allows developing an integrated, cross-sectoral understanding of complex systems. However, and especially for FCM based on individual interviews, the map-building process presents potential pitfalls. These are mainly related to the different understandings of the interviewees about the FCM semantics as well as the biases of the analyst during the elicitation and treatment of data. This paper introduces a set of good practice measures to increase transparency and reproducibility of map-building processes in order to improve credibility of results from FCM applications. The case study used to illustrate the proposed good practices assesses heatwave impacts and adaptation options in an urban environment. Agents from different urban sectors were interviewed to obtain individual cognitive maps. Using this set of data, we suggest good practices to collect, digitalize, interpret, pre-process and aggregate the individual maps in a traceable and coherent way.

Keywords fuzzy cognitive mapping; reproducibility; transparency; open science; participatory modelling

INTRODUCTION

Transparency and reproducibility are two essential characteristics of scientific studies. The scientific readership is increasingly demanding the full disclosure of original data and details about the methods and the analysis itself. It is not only the replicability of the results but also the growing demand of evidence-based policy that reinforces the importance of transparency. Disclosure, pre-analysis plans and open data are three elements critical to strengthen open science

*Correspondence to: Marta Olazabal, Basque Centre for Climate Change, BC3, Edificio sede, Planta 1, Parque Científico UPV/EHU, Barrio Sarriena s/n, 48940 Leioa (Bizkaia), Spain.
E-mail: marta.olazabal@bc3research.org

Received 11 May 2017
Accepted 6 May 2018

for credible decision-making (Miguel *et al*., 2014). Disclosure consists of systematically reporting key details about the data collection and the analysis and allows other researchers to replicate results and build on current studies, therefore improving scientific progress (Dafoe, 2014). The pre-analysis plan elaborates the standards for the study design with regards to the sample size, data handling or inclusion rules. Open data and materials provide the means to test, reproduce or extend the research, so that results are refutable and credible (Krugman, 2013; Dafoe, 2014).

Providing transparency and reproducibility not only benefits the readers who want to compare findings, learn and build on research outcomes but also benefits the authors in reducing their research biases (MacCoun and Perlmutter, 2015). Aiming at transparency and reproducibility helps to avoid self-biases such as pursuing mainly supporting evidences, extracting signals from random patterns, taking for granted expected results or focusing on post-hoc 'stories' to justify non-significant results (Nuzzo, 2015). For this reason, transparency and reproducibility turn out not to be just the responsibility of scientists but also of the institutions and journals that publish their work (Russell, 2013; McNutt, 2014).

The issue of transparency and reproducibility is more problematic in social and integrated sciences where the evaluation of the reliability of findings might be challenging and thus jeopardize the credibility of the studies for decision makers. However, many complex and dynamic real-life problems cannot be solved with quantitative approaches, either because there is a lack of data or because the data is qualitative (Obiedat and Samarasinghe, 2016). This challenge often calls for the use of methods based on expert elicitation or participatory processes that help understand systems that are characterized by data scarcity, scattered knowledge among multiple agents or high complexity (Olazabal and Reckien, 2015; Obiedat and Samarasinghe, 2016).

In contrast to quantitative data-driven methods (Hewitt and Escobar, 2011), a method based on a participatory process and expert elicitation is more likely to be questioned for transparency and reproducibility issues (Voinov and Bousquet, 2010). Among the variety of methods used in participatory systems modelling to formalize knowledge, in this paper, we particularly focus on fuzzy cognitive mapping (FCM) for its increasing application as a system mapping method (Papageorgiou and Salmeron, 2013; Jetter and Kok, 2014; Olazabal and Pascual, 2016).

FCM is a systems mapping method applied to a wealth of disciplines dealing with complex decision environments from socio-ecological (e.g. Gray *et al*., 2015) to financial (e.g. Mezei and Sarlin, 2016). Likewise, FCM is increasingly used to deal with transdisciplinary problems such as, e.g. climate change (Reckien, 2014; Kok *et al*., 2015; Olazabal and Pascual, 2016; Olazabal *et al*., 2018) as a means to integrate different kinds of knowledge to get a better understanding of phenomena and alternative action pathways. FCM captures expert knowledge developing a holistic view of the system that allows identifying interrelations among elements which would have been difficult to recognize otherwise (Mezei and Sarlin, 2016). FCM has important contributions to decision-making environments: It is a method that allows the integration of multiple expert perspectives (Olazabal and Pascual, 2016), it allows characterizing systems in data scarce environments (Reckien, 2014), it helps to understand the complex structure of a real system characterized by quantitative and qualitative elements (Mehryar *et al*., 2017), and it allows scenario building (Kok, 2009).

The FCM community has touched upon issues related to traceability in FCM building (e.g. Vanwindekens *et al*., 2013) or started to collect common difficulties and pitfalls in FCM practices (Jetter and Kok, 2014), and there have been proposals to solve technical difficulties for individual map aggregation and condensation (Mourhir *et al*., 2016; Obiedat and Samarasinghe, 2016). However, these authors also detect space for improvement at least in the reporting of source data, collection and treatment methods. More formal approaches are definitively required to make these studies more reliable. This is particularly true in cases where the final FCM is obtained from maps elicited in individual interviews with experts and stakeholders (hereafter, agents) (Jetter and Kok, 2014). First, because elicited data require an extensive treatment process (maps need to be aggregated) and, second, because the final output is used to simulate scenarios to be used for decision-making (Penn *et al.*, 2013).

The aim of the paper is thus to perform a revision of the FCM map-building process based on individual interviews so as to identify the potential pitfalls that may hinder transparency and reproducibility of FCM studies and suggest a set of good practices to overcome them.

We start the paper by analysing caveats in current FCM building practice particularly focusing on an example on socio-ecological applications where the FCM community is exponentially growing (Papageorgiou and Salmeron, 2013; Olazabal and Pascual, 2016). We then identify pitfalls and guide the reader through a set of suggestions to improve the traceability and coherency in map building as a means of guaranteeing transparency and reproducibility (section on "Proposal to increase transparency and reproducibility when combining fuzzy cognitive 3 maps").

We discuss the proposed measures through a case study on the impacts of heatwaves in an urban context (section on "Illustrative FCM study on urban climate change adaptation") and propose a good practice approach on how to disclose all data and tools. The user of the final model is able to visualize the entire process that leads to the final model and is able to access all of the intermediary outputs using Supporting Information (SM1–12). We discuss the findings and offer conclusions on the relevance of this contribution in the "Conclusions" section.

FUZZY COGNITIVE MAPPING: COMMON PRACTICE AND CAVEATS

Previous scientific literature offers the interested reader detailed insights into the structure of FCM, its construction methods and performance indicators (e.g. Kosko, 1986; Özesmi and Özesmi, 2004; Penn *et al.*, 2013; Jetter and Kok, 2014). In FCM, concepts relate to each other through directed, signed and weighted arrows representing causal relationships, thus forming a cause-and-effect diagram. Their graph structure allows systematic causal propagation and the addition of complementary knowledge by merging different maps (Kosko, 1986). FCM can thus be used to provide an all-inclusive and integrated lens on the 'perceived' mechanisms of a system.

Aiming at improving decision-making processes, FCM may be used to capture individual or shared knowledge environments (Langfield-Smith, 1992). Common practice in knowledge elicitation for FCM building expands on three options (combined approaches are also possible, refer to Jetter and Kok, 2014): (i) The analyst team (i.e. group of analysts responsible for the FCM study development) builds the map directly based upon their own technical or scientific knowledge, (ii) the analyst team builds the map based on knowledge elicited from agents (system experts or stakeholders that participate in the study providing their knowledge) or (iii) the analyst team reviews existing documents or datasets to build the map (i.e. data-driven FCM).

Following the second option (ii) where participation from agents is required, there are two main modes in which an FCM can be built (refer to discussion in Gray *et al.*, 2014): either as a group exercise (social or collective FCMs resulting from a group modelling exercise) or by combining information obtained from individual interviews.

The first mode (group exercise) aims to obtain consensus on how the system under study functions and to identify the most influential elements of such system. Maps are jointly built by a selected group of agents through a series of workshops or focus groups (refer to, e.g. Gray *et al.*, 2015). This can lead to a reasonable level of reproducibility and interpretability being based on intersubjective knowledge and consensus building. This type of group-based building of FCM reduces misunderstanding, increases coherency and facilitates knowledge exchange (Hobbs *et al.*, 2002; Jetter and Kok, 2014). However, it may reduce the potential richness, diversity and complexity that could

DOI: 10.1002/sres.2519

be elicited, given that participants are focused on reaching consensus instead of expressing the intricacies of their individual understandings. The group-based mode also includes the risk of powerful agents dominating the process and therefore introducing bias.

The second mode (individual interviews) is used when the analyst is interested in acquiring wider and deeper knowledge about how a specific system works (refer to, e.g. Olazabal and Pascual, 2016) rather than on searching consensus among stakeholders. However, this method requires the analyst to interpret, pre-process and aggregate individual maps after these have been collected. The high level of heterogeneity makes this option especially exposed to questions related to transparency and reproducibility. Two main issues may alter results or threaten coherency in FCM that are based on individual interviews: (i) the different understandings of the interviewees about the FCM methodology itself (mainly related to the semantics of 'concepts' and 'relations') and (ii) the biases of the analyst when interpreting, analysing and aggregating maps that may involve (un)intended manipulations of maps to support pre-conceived theories about the system under analysis. Because of the intrinsic nature of participatory processes, neither of these two issues can be completely avoided, but through adequate documentation, they can be made as explicit as possible. We propose ways to do this in our paper.

In the next section, we extend the approach by Özesmi and Özesmi (2004) and suggest explicit ways to improve transparency and reproducibility for the most critical steps in FCM building processes for studies based on individual interviews.

PROPOSAL TO INCREASE TRANSPARENCY AND REPRODUCIBILITY WHEN COMBINING FUZZY COGNITIVE MAPS

As an extension of Özesmi and Özesmi (2004), we illustrate the step-by-step FCM building process detailing intermediate processes and outputs (Figure 1).

In step 1, the problem is defined by the analyst who formulates the question to be asked to the participants according to the scope and objectives of the study. Step 2 entails the elicitation process. Participants are identified and invited to take part in the study. Then, the interview process is designed. Interviews are conducted, either face to face or virtually, and individual maps are drawn. Step 3 includes the digitalization, interpretation and pre-processing of individual maps by the analyst. Step 4 deals with the homogenization across the set of individual maps. Homogenization in this case refers to the definition of a common terminology across maps and the choice of a common level of detail to which the problem will be modelled. Later on, individual maps are combined to produce the final map (step 5).

The final aggregated map is usually used in two ways. It can be analysed as a complex network (so-called static analysis), or it can be used to test different scenarios (so-called dynamic analysis) (for further reading, refer to Özesmi and Özesmi, 2004; Jetter and Kok, 2014) which allows responding to what if questions (Carvalho, 2013; Mezei and Sarlin, 2016). In this paper, we focus on the so-called static analysis, steps 1 to 5 (map building process depicted in Figure 1), which is a preliminary step before running a scenario analysis (for further reading, refer to Kok, 2009). Steps 1 to 5 are the steps most vulnerable to self-biases and where risks for the credibility of final results are most likely to occur. To fill this gap, we list potential pitfalls and make suggestions to overcome them (Table 1). We highlight the most critical methodological steps (column A) and sub-steps (column B) in relation to improving transparency and reproducibility. We identify potential pitfalls (column C) and suggest ways to address them (column D). We also suggest materials and documentation of methods to be provided (column E). To illustrate the potential of our proposals we build and show these materials in form of Supporting Information (SM1–SM12) for an illustrative case study (column F) whose results and detailed analyses are described in the section on "Illustrative FCM study on urban climate change adaptation".

DOI: 10.1002/sres.2519

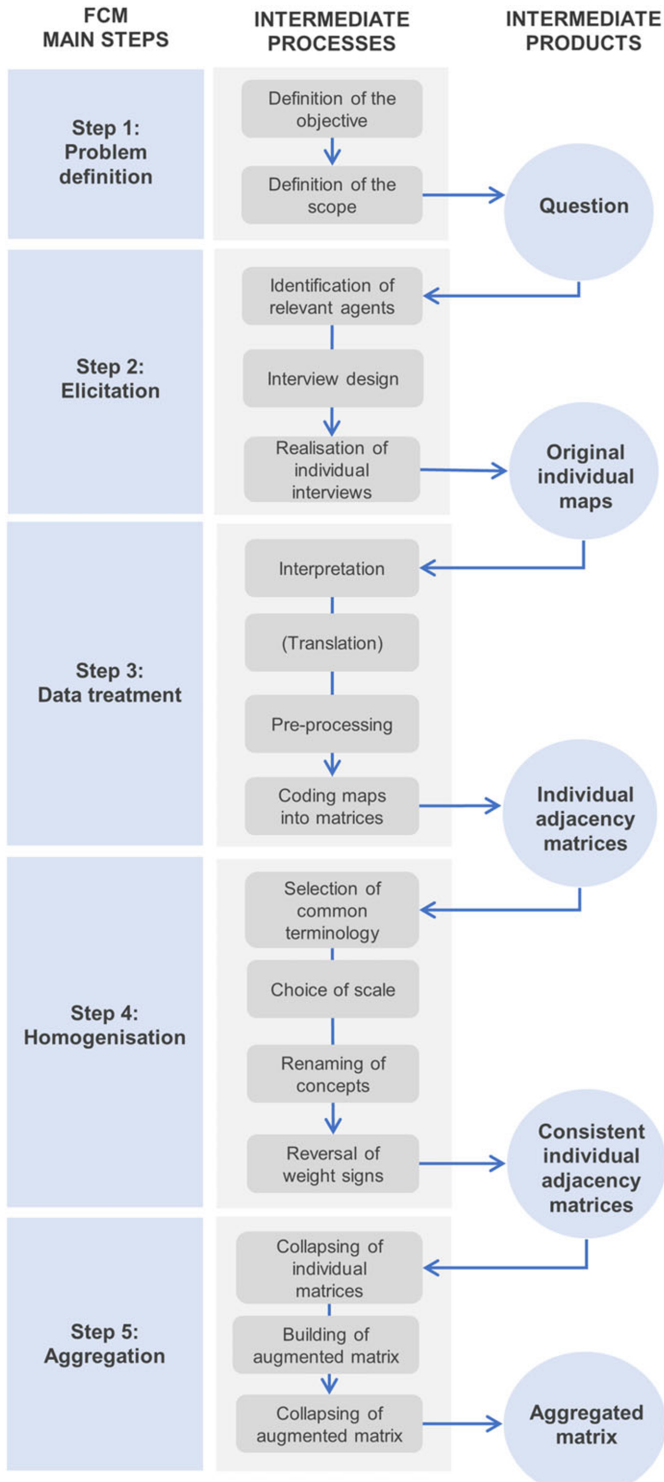

Figure 1 Detailed process and intermediate products of a fuzzy cognitive map (FCM) building exercise

Syst. Res (2018)
DOI: 10.1002/sres.2519

Table 1 Strengthening reproducibility and transparency in FCM

A	B	C	D	E	F
Steps	**Critical sub-steps**	**Potential pitfalls**	**Approaches to strengthen reproducibility and transparency**	**Material and methods suggested**	**Examples**
Step 1: problem definition	Definition of research objective	- Setting a too narrow scope that restricts the input from stakeholders (Jetter and Kok, 2014). - Unstructured and incoherent definition of the system under analysis leading to ambiguous final map.	- Define the boundaries of the system (temporal, spatial, sectoral) according to the problem identified.	- Workshop with stakeholders involved in the management of the system - 'Model boundary chart' (Sterman, 2000 cited in Jetter and Kok, 2014) - Description of the case study context and the system boundaries.	Section entitled "Step 1: Problem definition"
Step 2: elicitation	Selection of relevant agents	- Ignoring important cause–effect relations, jeopardizing objectivity and validity of the results (Papageorgiou and Salmeron, 2013).	- Identify required knowledge domains. - Identify types of stakeholders (civil society, decision-makers, researchers and academia, private sector…). - Ensure a minimum number of participants (Özesmi and Özesmi, 2004 suggest a minimum of 20).	- List with characteristics of participating stakeholders.	SM1: list of participating agents.
	Interview	- Maps do not represent cause–effects relations of the system under analysis. - Participants use different scales to evaluate problems (Papageorgiou and Salmeron, 2013).	- Define clear and unambiguous questions. - Prepare an interview guideline and follow it with each participant without deviations. - Help participants to clearly understand the FCM methodology	- Interview guideline or clear description on how the interview was conducted. - Original maps as drafted by the interviewees.	SM2: interview guidelines. SM3: original data collected.

(*Continues*)

Table 1 (Continued)

A	B	C	D	E	F
Steps	Critical sub-steps	Potential pitfalls	Approaches to strengthen reproducibility and transparency	Material and methods suggested	Examples
		- Incoherencies within individual maps.	(semantics of concepts, arrows and weights). - Check and confirm the meaning of each new addition to the map. - Record the interview (audio/video); take notes during the interview.	- Notes of the interviews.	SM4: notes taken during individual interviews.
Step 3: data treatment	Pre-processing	- Distorting original knowledge, perceptions or experiences translated by participants, by introducing bias by the analyst.	- Maintain original meaning and connotations to guarantee a coherent interpretation. - Track every change or modification during the pre-processing. - Interpret maps using notes and recordings of the interviews. - Validate changes with notes/recording and/or with participants. - Make sure that the interviewer leads the data treatment.	- List of both original and of translated concepts[a] - Original digitalized matrices - Evidence about any change or modification affecting any of the original matrices	SM7: FCM workbench for manipulation of original concepts (column C and D) SM6: adjacency matrices of individual maps SM7: workbench for manipulation of original concepts (columns C to H)
Step 4: homogenization	Selection of common terminology	- Unstructured homogenization can lead to double counting, irrelevant or groundless relations in the final map. - Ambiguous or erroneous interpretation of the final aggregated map.	- Track every change made in the process of homogenization. - Select a consistent terminology across maps. - Reverse signs where needed.	- Material and/or methods used to define how concepts have been renamed and groups created (e.g. using "Grounded Theory" as proposed by Reckien, 2014).	SM7: workbench for manipulation of original concepts (columns F and G)

(*Continues*)

DOI: 10.1002/sres.2519

Table 1 (Continued)

A	B	C	D	E	F
Steps	**Critical sub-steps**	**Potential pitfalls**	**Approaches to strengthen reproducibility and transparency**	**Material and methods suggested**	**Examples**
			- Interviewer(s) participate(s) in the homogenization process. - Develop accumulation curves of new concepts to validate the sample size.	- Information about which weight signs have been reversed because of homogenization. - Accumulation curve (Özesmi and Özesmi, 2004).	Refer to Figure 3
	Choice of level of detail: grouping and ungrouping of concepts		- Track every change made in the process. - Specify the level of model detail ungrouping or grouping of concepts depending on the objectives of the research. - Define the meaning and context for each final concept to facilitate interpretation. - Interviewer(s) participate(s) in the homogenization process.	- Information about how concepts have been renamed and about the groups created. - Interpretation/ definition of each of the concepts in the final map.	SM7: workbench for manipulation of original concepts (columns F and G) SM8: lists of concepts in the aggregated map and their interpretation
Step 5: aggregation	Collapsing of matrices	- Incoherent connections in the final aggregated map leading to irrelevant, inaccurate or groundless results when using the final model for scenario analysis. - Incoherencies between the information collected and the final output.	- Define how the weights are averaged when grouping concepts. This applies to individual matrices and to the augmented matrix. - Identify potential incoherencies: two concepts connected with different directions or	- Information about the collapsing technique and its program code.	SM9: individual adjacency matrices after step 4 And SM10: R code for augmenting and collapsing matrices and for quality and

(Continues)

Table 1 (Continued)

A	B	C	D	E	F
Steps	**Critical sub-steps**	**Potential pitfalls**	**Approaches to strengthen reproducibility and transparency**	**Material and methods suggested**	**Examples**
			with different weight signing. - Select an action to be taken for each identified incoherency. Document the action. - Interviewer(s) participate(s) in the aggregation process.		redundancy checks for final matrix/map
				- Final aggregated map in an easy-to-handle format, e.g. in a spreadsheet with graph visualizing capacities.	SM11: aggregated matrix; matrices for mean, standard deviations and sign changes of weights. And SM12: final aggregated map in NodeXL format (Social Media Research Foundation, 2014)

[a]Step required depending on the language in which results would be disseminated.

DOI: 10.1002/sres.2519

ILLUSTRATIVE FCM STUDY ON URBAN CLIMATE CHANGE ADAPTATION

The aim of this section is to illustrate Table 1 through a complete case study process. The case study had the objective of exploring direct and indirect impacts of heatwaves and potential climate change adaptation strategies in an urban context. The goal was to elicit transdisciplinary knowledge (different research disciplines and different policy sectors) on impacts of heatwaves and adaptation options in a specific urban environment (city of Madrid, Spain). The output of this FCM building exercise is used in a second stage to build scenarios of urban policy options (adaptation measures) considering cascading cross-sectoral effects. Providing credibility to the full process of data elicitation and treatment is therefore critical to rely on the results of the scenarios. The experiment is reported following the consolidated criteria for reporting qualitative research (COREQ) (Tong *et al*., 2007). For the interpretation and discussion of the results in the specific context of climate change adaptation, we refer the reader to Olazabal *et al*. (2018).

Step 1: Problem Definition

Defining the problem both from a scientific and stakeholder point of view is critical to understand the boundaries and the scope of the exercise and to understand the interests and objectives of each one of the final users of the outputs (Lang *et al*., 2012). Failing to define the problem under study in an unambiguous way can lead to "all-encompassing, overly complex models" (Jetter and Kok, 2014, p. 49) that are not useful to address stakeholder needs. Importantly, the definition of the problem will greatly influence stakeholders' selection (section on "Identification of relevant agents" below) and the framing of the question which will guide the FCM interviews with participants (refer to section on "Interview design").

Different approaches and methods can be used for problem definition in FCM. For example, Mourhir *et al*. (2016) and Mehryar *et al*. (2017) use a mix of methods including a DPSIR model (driving force, pressure, state, impact and response), workshops and literature reviews to define the problem and research questions. The problem for our case study was defined through a workshop in the framework of the European project Bottom-up Climate Adaptation Strategies for a Sustainable Europe (BASE). Eleven agents from different sectors (water, energy and agriculture) participated including private and public agents at different action levels (national, regional and local). The workshop aimed at identifying vulnerabilities and potential adaptation pathways for heatwaves and droughts in the regional area of Madrid. Among other strategic actions, results pointed out the importance of the impact of heatwaves on health at city level and the deployment of green infrastructures as a potential adaptation option. This workshop set the scene to develop a specific case study in the city of Madrid. In order to capture higher amounts and more diverse information, the approach selected was to elicit individual FCM maps from participants with relevant knowledge and experience on the impacts of heatwaves at urban level and specifically, in Madrid. The initial workshop pointed out the importance of considering not only urban agents but also agents at higher decision-making levels as their policy options can impact the urban systems. The study therefore also contemplates multilevel interactions elicited from stakeholders at regional or national level.

Step 2: Elicitation

Identification of Relevant Agents

In FCM studies, participants are selected based on their expertise and knowledge about a specific issue. The objective here is not to obtain a representative sample of a population but to represent different knowledge areas. There is a variety of tools that can be used to identify relevant agents such as snow ball sampling, stakeholder analysis or organizational network analysis (Jetter, 2006; Reed, 2008).

We identify two different but complementary strategies that could be used for this purpose: (1) selecting agents with similar expertise at the

DOI: 10.1002/sres.2519

same scale so as to obtain robust information on the functioning of a sub-system and identify incoherencies and disagreements or (2) selecting agents with expertise in different areas of knowledge and/or at different scales so as to collect the most diverse and complete information about how a system functions.

Because, in our case study, the underlying objective is to map the widest range of interdependencies between urban sectors in order to identify direct and indirect impacts of heatwaves, participants were identified according to the second strategy. Participating agents were selected according to (i) multiple sectors (or knowledge areas) that potentially exhibit interactions during heatwaves (health (9 agents), urban planning and design (4 agents), green and blue infrastructures (4 agents) and climate change (5 agents); (ii) professional perspectives (scientists, decision makers and technical experts) and (iii) levels of decision-making (local, regional, national). In some cases, there are limits to providing detailed information on the selected agents because of confidentiality (SM1).

Interview Design

The interview needs to be designed in alignment with the research objective (refer to examples in Isak *et al*., 2009; Reckien, 2014): (i) The objective must be translated into understandable and unambiguous interview questions and (ii) if multiple objectives are pursued in the same interview, this needs to be incorporated in an explicit way. The interview designed for our illustrative case study consisted of two stages (refer to interview guidelines in SM2) (other examples of guidelines in, e.g. Reckien, 2014).

First, all participants meet separately in person with the interviewee and are asked to develop a map, that according to their perception, experience and knowledge, responds to the question "*what are the impacts of heat waves in the city of Madrid?*". In a second round, they are asked to identify the adaptation measures that would perform best to reduce the identified impacts: "*Which measures could help to compensate or mitigate (reduce) the impacts of heatwaves at short, medium or long term?*" In this second round, stakeholders may respond in two different ways: (i) adding new concepts to the map or (ii) identifying concepts already existing in their map as adaptation measures.

Conducting Individual Interviews

Meaningful definitions of map concepts (Jetter and Kok, 2014) as well as a full understanding of FCM semantics (Carvalho, 2013) are required. We used a free-association technique rather than pre-defined concepts (refer to Gray *et al*., 2014; Jetter and Kok, 2014). The latter mode may activate memory (Jetter and Kok, 2014) and facilitate homogenization (refer to step 4); however, it may also inhibit stakeholders' reasoning and introduce bias because of the pre-conceptions of the analyst. For this reason, we used the first approach of free association where participants are free to choose any concept and express it in their own words, in contrast to a process where concepts are pre-established by the analyst (e.g. using structured questions with pre-selected options).

We found that providing instructions that help participants to understand FCM semantics through the available components (concepts, links and weights) along with an example is helpful (refer to guidelines in SM2 where we included an example on the impact of urban development on water reservoirs). Such instructions should include guidance to guarantee that both concepts and links represent variables that can take on different values along a gradient (Carvalho, 2013).

In Table 2, we suggest some ways to improve coherence within and between individual maps which are specifically related to how concepts, links and weights are explained and understood during interviews. When requested by the interviewee, the interviewer may take the lead and translate the discussion into the map (e.g. Reckien, 2014). This was often the case in our study where participants generally showed little confidence in their own initiative. To increase the traceability of this mapping process, the original maps should be made available. SM3 contains maps as drafted by participants together with the analyst's notes taken during the interviews. SM4 includes any annotations that the

DOI: 10.1002/sres.2519

Table 2 Suggestions to strengthen coherency in the elicitation phase

	Definition	Suggestions to strengthen coherency
Concepts	Concepts (also known as nodes, factors or variables) are elements or entities of the system.	- Participants are asked to include only concepts that may reflect a gradient. This prevents from having concepts in the map that cannot "integrate the effects of the causal changes modelled by the relations" (Carvalho, 2013, p. 2459).
Links	Links (also known as arrows, edges, arcs or connections) indicate the presence, sign and direction of cause–effect relationships.	- Participants are asked to consider each link separately, i.e. effects of previously connected concepts should not be taken into account. - It is also advisable to offer positive or negative linear causalities to avoid the cognitive strain on participants (Jetter and Kok, 2014)
Weights	A weight reflects the strength of the connection between two concepts, and it is represented by a value on a linguistic or numerical scale.	- Participants are reminded that the assigned weight does not refer to percentages, correlations or probabilities. - Participants need to assign weights based on what they believe the strength of the cause–effect relationship is. However, it is not always possible to fully separate such a belief estimate from the confidence about the estimate. - Participants are reminded to contextualize weights for the case study.

interviewer deemed useful for future interpretation and analysis.

Step 3: Data Treatment

Many of the non-transparent and non-reproducible aspects of FCM are hidden in this step. Decisions taken here are often poorly documented, and clear arguments are missing. The data treatment process starts once all individual maps are collected. First, the analyst digitalizes the individual original maps by converting them into adjacency matrices (refer to didactic examples in Özesmi and Özesmi, 2004; Kok, 2009) (examples from the case study in SM5). The analyst carries out a pre-processing of each of the individual maps which can be later digitalized (SM6).

Pre-processing activities include all manipulations on original individual maps as drafted by the agents, as a result of a process of interpretation by the analyst and validation with the agents. Jetter and Kok (2014) refer to these activities as post-processing activities (activities following knowledge elicitation processes) that involve model adjustments to enable proper FCM computation and meaningful model interpretations. They list the following cases for model adjustment (ibid.):

- Disregard for model boundaries as defined in step 1 (problem definition)
- Overdetailed causal links, i.e. when a participant describes a concept in too much detail.
- Inclusion of 'receiver' concepts, i.e. when a participant includes a concept that has no outgoing arrows. According to Jetter and Kok (2014), this is a sign of incomplete knowledge although these concepts can be used as diagnostic variables for the calibration of FCMs.
- Inclusion of conditional causality, i.e. when a participant includes a relation that is conditional.
- The presence of time lags, i.e. when a participant introduces relations that span different timeframes (Park and Kim, 1995).

In our case study, pre-processing of individual maps have entailed the following cases:

- Redundant information: Concepts and relations which are basically conveying the same

DOI: 10.1002/sres.2519

information should be removed. For example, in map #20 (refer to Figure 2a, SM3), the interviewee connects various concepts ('data/forecasts', 'regional climate projections' and 'information/knowledge/tools') and assigns a weight of 1 to the connections. This is a sign of redundancy as one (information/knowledge/tools) includes the other two.
- Deviations from FCM method: e.g. when the analyst suspects that concepts or relations cannot be represented by variables of when relations do not represent cause–effect relationships (as described in Table 2). For example, participant #15 links 'residential water demand' and 'municipal services water demand' with 'urban water demand' (weight 0.6 and 0.4 respectively). This does not reflect a cause–effect relationship but two fractions (refer to Figure 2b, SM3).
- If the information is collected in a language different from the language in which scientific results will be communicated, this requires translation (Spanish to English in our case). Here, the most critical aspect is not losing any implicit meaning or cultural connotations embedded in the terminology.
- Minor adjustments such as typos can be validated through the notes (SM4) and recordings taken by the interviewer or with the participants.
- Consideration must be given to anonymity. Participants may prefer not to be recorded. In this regard, making information available and building a transparent process are important to create a trustful environment.

As mentioned earlier, many of the caveats for transparency and reproducibility of FCM studies emerge from not performing an explicit and traceable data treatment process in this step. Not identifying adequate pre-processing needs in individual maps may lead to inaccurate, uncoherent final outputs and increase the potentiality of misleading decisions based on those outputs. Some freeware tools such as FCMapper (Bachhofer and Wildenberg, 2009) allow tracking part of the information, but not in a structured manner, and it is almost never reported.

Our suggestion here is to develop a unique 'workbench' listing the entirety of concepts encountered in all the interviews and collecting the information on how these have been pre-

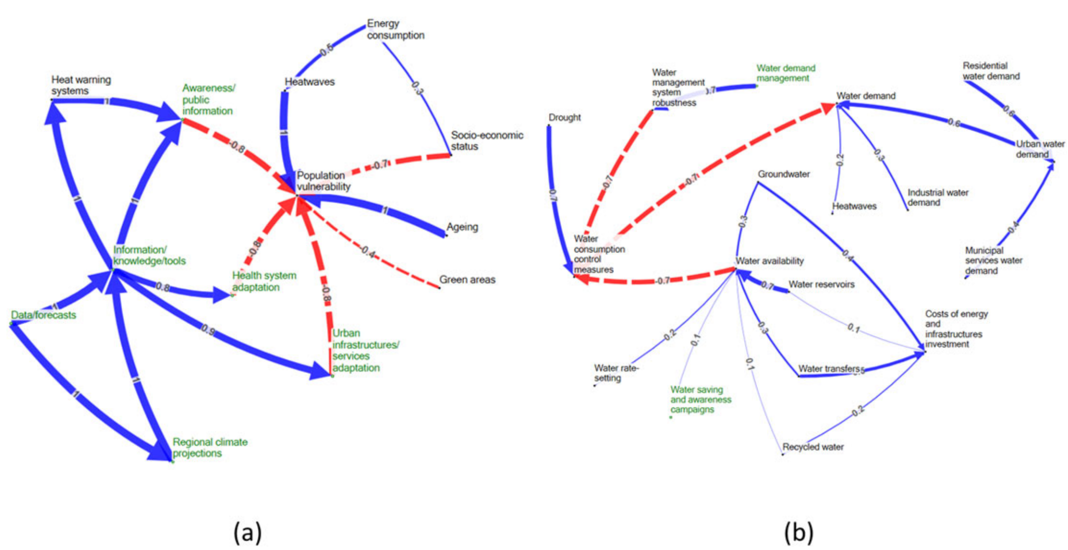

Figure 2 Examples of maps requiring pre-processing: redundant information (a, participant #20) and deviations from FCM method (b, participant #15). Solid blue arrows denote positive connections; dashed red arrows denote negative connections; the thickness of the arrows denotes the strength (weight) of the connection. Adaptation measures identified by the participants are indicated with green nodes and text. Produced with NodeXL software

DOI: 10.1002/sres.2519

processed. In this way, every decision taken by the analyst can be tracked back to the original maps. This material can easily be shared and compared. Our 'workbench' (refer to SM7 and examples in Table 3) provides information on the 380 original concepts from the 22 original maps and allows to report on data treatment (step 3, this step) and step 4 of homogenization (developed in the section entitled "Step 4: Homogenisation") (Table 3, columns F and G). The workbench, exemplified in SM7, stands as the central logbook for tracking the entire map building process which is further expanded in step 4.

Step 4: Homogenization

Homogenization—also referred to as standardization (Gray *et al*., 2014) or, partially, as condensation or grouping (Özesmi and Özesmi, 2004)—relates to both the definition of a common terminology across maps (stage 1) and to the choice of a common level of detail to which the problem will be modelled (stage 2). Both stages aim at increasing the consistency of the terminology and the coherency of the structure in the final map.

Selecting a common terminology (stage 1) is required because participants can express the same idea in different ways or different ideas in the same way. It is important that a single analyst conducts all interviews and that the same analyst leads the processes of data treatment, homogenization, aggregation and analysis. If different analysts conduct interviews but do not participate across the full FCM building process, the risk of losing important connotations or misinterpreting concepts and/or connections increases. In general, the process of homogenization in stage 1 implies a grouping of concepts that have the same meaning and selecting a common and consistent wording across maps (in the case study, e.g. 'green areas', 'green spaces', 'urban green areas', 'parks'… all renamed as 'urban parks') provided that is what they are referring to in all in each of the maps. In other cases, it may also imply a rewording of a concept to reflect the original idea (e.g. participant #6 included 'social services' in his/her map but he/she meant 'social impact prevention measures and policies' as interpreted by the analyst during the interview and validated with participant #6). Importantly, when the analyst renames a concept using an antonym (e.g. 'health' is renamed by 'morbidity'), the signs of connections need to be reversed. For this process, using the notes taken during the interview (refer to SM4), the analyst can assess how the expertise and background of the participants (refer to SM1) influences their use of terminology.

The choice of a consistent level of detail (stage 2) requires the analyst—in agreement with the final user(s)—to decide the level of generalization or specialization that the final map will convey. Based on that, this will require to group or ungroup concepts. In the case study, it was mostly necessary to 'zoom out' (reduce the level of detail) to solve unbalanced terminology (e.g. include 'trees' within 'green infrastructures'). In another example, morbidity was used as a term to group 'allergies', 'waterborne outbreak', 'foodborne outbreaks', 'legionellosis', 'cold', 'thermal stress', 'dehydration', 'anuria', 'disorientation', 'heatstrokes', 'burns', 'physical activity health improvement',[1] 'asthma/cold propensity' and 'tuberculosis/legionella propagation'. One can envisage the case where the analyst wishes to 'zoom in', i.e. to get a higher resolution of a specific phenomenon. For instance, the concept 'morbi-mortality' was mentioned by several participants in our example (participants #2, #4 and #21). If the analyst decides to analyse 'morbidity' and 'mortality' separately, as it is the case of our example, morbi-mortality should be ungrouped. In this case, the incoming and outgoing connections must be duplicated. Other examples can be found in the workbench SM7.

The workbench SM7 is now expanded during step 4 (treatment and homogenization) with renaming and (un)grouping into the final 87 concepts. It also informs whether those changes imply a change of the sign of the incoming and outgoing connections.

It should be noted that it is the analyst who decides which degree of complexity to reveal. Based on our experience, there exists a trade-off between the desire of adequately capturing complexity and the need of simplicity to facilitate

[1] Sign of connection is reversed. See expanded information in SM7.

DOI: 10.1002/sres.2519

Table 3 Structure of the suggested workbench and examples

A	B	C	D	E	F	G	H
Var ID	Map ID	Original concept	Translation	I or A (impact or adaptation)	Homogenization stage 1 (terminology)	Homogenization stage 2 (scale)	Comments (deletions, duplications, change of sign)
#9	#1	Salud	Health	I	Morbidity	Morbidity	Change of sign
#41	#2	Servicios sociales (planes de alerta)	Heat-warning plans	A	Effectiveness of heat-warning plans	Heat-warning systems	
#155	#9	Aislamiento viviendas	Thermal insulation of dwellings	A	Thermal insulation of buildings	Climate-sensitive planning and design	
#268	#16	Superficie vegetal/agua	Green/blue areas	A	Urban parks and gardens	Green infrastructures	Participant refers to urban parks and water bodies. Ungroup: one green infrastructure and one blue infrastructure

the interpretation of the final aggregated map. In that sense, the homogenization step is critical as some concepts and connections between concepts might be removed or combined as a result of it. Using a technique where the concepts are predefined by the interviewer would avoid the need of homogenization and thus reduce potential misinterpretations, but as already stated above, it would also reduce diversity and broadness of collected knowledge. Traceability in this step is required in order to be able to replicate the study under different terminology and scaling choices.

It is also helpful to provide a glossary for the concepts to be included in the final aggregated map (step 5). This avoids ambiguities and facilitates an adequate interpretation of the results by end-users or by researchers aiming to replicate the study. The use of the glossary is illustrated in SM8.

Eventually, once all individual maps have been interpreted and homogenized, the adequacy of the sample size should be assessed. We suggest to follow the approach of Özesmi and Özesmi (2004) who analyse the incremental addition of information as new maps are added. A stabilization of the curve indicates that adding new participants to a sample would not add substantial new knowledge to the problem representation. For our example, we compare this so-called accumulation curve (Figure 3, darker area) against the total number of concepts (lighter area, Figure 3).

Formal approaches to homogenization are important to increase transparency and reproducibility of FCM studies. They are also important to strengthen internal coherency of the FCM building process ensuring that only concepts that reflect the same ideas are combined (Jetter and Kok, 2014). In an example from our study, 'air conditioning (AC)' is positively linked to morbidity. However, some participants argued that AC decreases indoor temperature and thus decreases morbidity related to heat stress (i.e. negative relation). Others argued that AC increases the susceptibility towards infections (common cold), implying a positive relationship with morbidity. Both are initially valid and meaningful but because of the homogenization process (refer to example of morbidity earlier where all potential health problems are grouped), they might end up being ignored (intentionally or not).

DOI: 10.1002/sres.2519

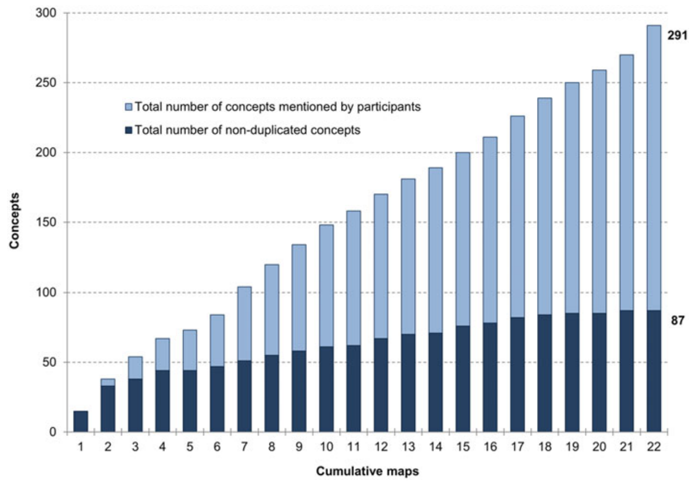

Figure 3 Accumulation curve: number of maps (accumulated) vs. number of concepts mentioned

Step 5: Aggregation

The process of aggregating the individual maps into one large map involves three main processes (refer to step 5 in Figure 1): (i) in each individual adjacency matrix, internal collapsing of concepts that belong to the same group, (ii) building of the augmented matrix from individual matrices and (iii) collapsing of concepts belonging to the same group in the final augmented matrix.

First, the process of collapsing needs to be done for each individual map (internal collapsing) as some connections may appear multiple times after step 4 (section entitled "Step 4: Homogenisation"). If required, weights need to be assigned to existing duplicated connections resulting from the process of ungrouping (refer to the previous morbi-mortality example). In the collapsing process of individual and augmented matrices, weights are generally averaged. The analyst may also decide to weight agents or groups of agents differently, to include, for example, a credibility factor (Groumpos, 2010).

In the example, we reviewed and collapsed each individual matrix using spreadsheets (refer to result in SM9). Then, to build the augmented matrix and collapse it, we have developed a code in R (SM10). It uses as source data SM9 (individual maps as separate worksheets) and computes the final map (refer to result in SM11). To track this process and adequately interpret the results, we suggest to provide some additional metrics for interpretation of the final map: 'mean' is an $m \times m$ matrix (with m being the number of concepts, $m = 87$ in our example) with the average value of the weight for each of the existing connections in the final aggregated map (here, we work with credibility factors of one, i.e. each agent has the same weight). If a connection is active in multiple maps (i.e. it has been mentioned by multiple agents), the standard deviation 'sd' and the coefficient of variation 'cv' are computed to give an indication of spread between the weights given by different agents to that same connection. Values with high spreads should be checked by the analyst as they may point towards disagreements between experts or interpretation errors by the analyst. 'Count' provides the number of agents mentioning the same connection. 'Sign change' checks if an active connection has the same sign (positive or negative) in all individual maps. Sign changes are flagged, indicating, again, a potential inconsistency that should be checked. SM11 contains these $m \times m$ matrices for 'mean', 'sd', 'cv' and 'sign change' values.

Generally, sign changes between concepts can occur after the process of homogenization when concepts are grouped. For example, when (i) concepts are renamed (e.g. 'health' is renamed to 'morbidity') or (ii) participants follow a different

DOI: 10.1002/sres.2519

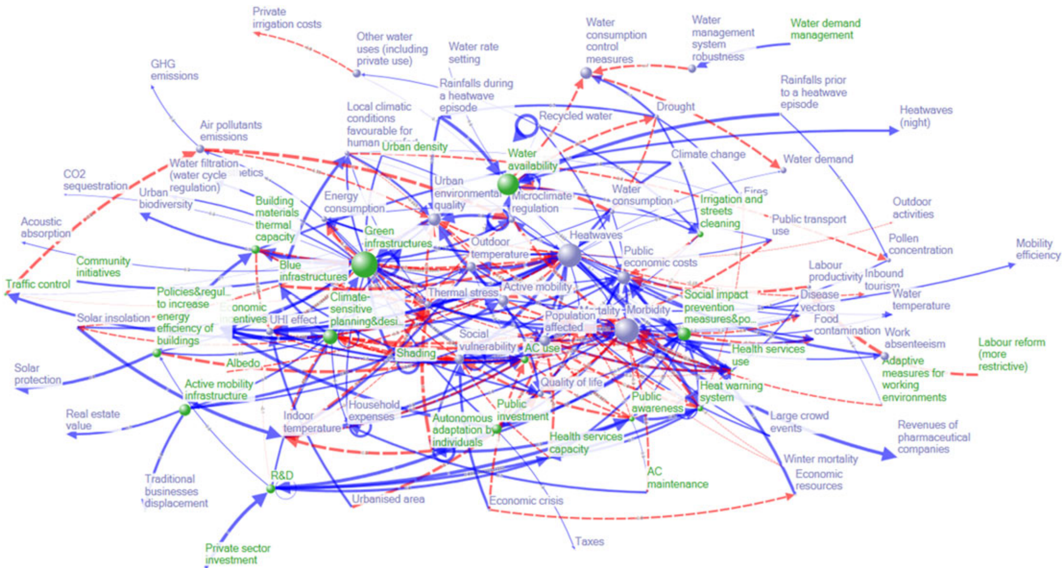

Figure 4 Visualization of final output: aggregated map (SM12). Solid blue arrows denote positive connections; dashed red arrows denote negative connections; the thickness of the arrows denotes the strength (weight) of the connection; the size of the nodes denotes their centrality (importance) in the map. Adaptation measures identified by the participants are indicated with green nodes and text. Produced with NodeXL software

reasoning when linking the same two concepts (e.g. air conditioning (AC) linked to morbidity described in the section entitled "Step 4: Homogenisation", in which case, the analyst may decide to keep both connections to stress these different cause–effect relations or to average the weights and track the information).

Positive or negative self-loops, that appear as non-zero diagonal values in the adjacency matrix, are of special interest. In the final aggregated map, 13 self-loops were found (refer to overall metrics in SM12). In our case study, we found, for example, that increasing green infrastructures promotes further actions to create more green infrastructures. Some other examples are 'autonomous adaptation by individuals', 'climate-sensitive planning and design', and 'health services use'. In all these cases, the self-loop represents a positive feedback of the concept on itself and is a result of the process of homogenization. Although this was not the case for us, participants could be allowed to include self-loops in their original maps. For scenario building, self-loops in the final aggregated map can be kept (Buruzs *et al*., 2014) or removed (Kosko, 1986).

Figure 4 shows the final output. Depending on the level of homogenization, systems can achieve more simple representations. However, when developing FCMs, there must be a balance between the understandability of the system and the robustness of the output for scenario building (Penn *et al*., 2013). If the objective is to capture the complexity and consider hidden cascading effects in decision-making processes, a certain level of complexity is required. Typically, it is impossible to capture this complexity through human perception. We strongly encourage to provide the final map as both a matrix and in an accessible format (such as an open source viewer). The matrix of connections and weights is shown in SM11 and visualized in SM12 (in NodeXL format). Through this visualization, the output can be more easily examined and discussed by researchers, practitioners or stakeholders whose feedback may be solicited for revisions.

CONCLUSIONS

Based on a step-by-step FCM building process, we suggest good practice measures to improve

DOI: 10.1002/sres.2519

transparency and reproducibility of FCM results. These suggestions ultimately intend to increase credibility of FCM results and comparability among different studies. To illustrate the usefulness of our proposals, we used a real case study that analyses the impacts of heatwaves and potential adaptation options in an urban setting. We propose which documents to provide, and we suggest that a single lead analyst directs the process and conducts all interviews to maintain coherency and reduce deviations from the original data. We also highlight the process of homogenization as a central and challenging step in FCM studies.

In general, disclosing more information in FCM would allow to better understand the diversity and broadness of collected knowledge and to adequately interpret the final output, both critical for reproducibility and effective applicability. For traceability, it turns out imperative to track all manipulations of the source data such as translation, renaming or adjustments in maps as the central piece of documentation of the FCM model building. Because FCM aggregation methods are not well agreed upon, it is also recommended to provide a full disclosure of any techniques used for this purpose.

We conclude that good practices for FCM map building should at least look at the following:

1 The provision of clear guidelines for building an FCM from individual maps (guarantees comparability among individual maps and reduces data treatment needs)
2 The use of a structured and understandable workbench for data treatment (guarantees traceability of potential changes)
3 A homogenization method aligned to scientific requirements and stakeholder needs (guarantees coherency and usability of the final output)
4 A replicable aggregation method built on clear aggregation rules (guarantees reproducibility)
5 Provision of metrics (e.g. mean, standard deviation) for concepts and connections (guarantees interpretability of final map).

Given the increasing use of FCM across disciplines and the growing call for transparency and reproducibility in science, we hope that our contribution is taken as a first step and opens up a reflection to advance towards good practice approaches for FCM building in particular and for participatory system modelling in general.

FUNDING

This study is part of the project Bottom-up Climate Adaptation Strategies for a Sustainable Europe (BASE) funded by the European Union's Seventh Framework Programme for research, technological development and demonstration under Grant Agreement No. 308337. MO (FPDI-2013-16631 and IJCI-2016-28835) and MBN (RYC-2013-13628) acknowledge co-funding from the Spanish Ministry of Economy, Industry and Competitiveness (MINECO).

ACKNOWLEDGEMENTS

We would like to thank Ana Iglesias, Luis Garrote and Pedro Iglesias from the Universidad Politécnica de Madrid (UPM) for their support in establishing contacts to the participants of this study. We are grateful to the 24 participants that devoted their time and shared their knowledge.

AUTHORS' CONTRIBUTION

MO, MBN and AC conceptualized the study. MO, MBN, SF and AC jointly designed the methodological approach. MO led the study, conducted the interviews, led the data analysis, prepared the supporting material (digitalized maps, spreadsheets…) and developed the displayed items shown in the manuscript (figures and tables). MBN developed the R code with the support of MO. AC coordinated various experiments in the regional area of Madrid where this FCM exercise is framed. MO prepared the original draft of the manuscript. All authors reviewed and edited the manuscript and the supplementary material provided with it.

DOI: 10.1002/sres.2519

REFERENCES

Bachhofer M, Wildenberg M. 2009. FCmapper—Fuzzy Cognitive Mapping Software Solution [WWW Document]. http://fcmappers.net (accessed 2.17.17).

Buruzs A, Kóczy LT, Hatwágner MF. 2014. Using fuzzy cognitive maps approach to identify integrated waste management system characteristics, in: 2014 5th IEEE Conference on Cognitive Infocommunications (CogInfoCom). Presented at the 2014 5th IEEE Conference on Cognitive Infocommunications (CogInfoCom), pp. 141–147. doi:https://doi.org/10.1109/CogInfoCom.2014.7020435

Carvalho JP. 2013. On the semantics and the use of fuzzy cognitive maps and dynamic cognitive maps in social sciences. *Fuzzy Sets and Systems* **214**: 6–19. https://doi.org/10.1016/j.fss.2011.12.009

Dafoe A. 2014. Science deserves better: the imperative to share complete replication files. *PS: Political Science & Politics* **47**: 60–66. https://doi.org/10.1017/S104909651300173X

Gray SA, Zanre E, Gray SRJ. 2014. Fuzzy cognitive maps as representations of mental models and group beliefs. In *Fuzzy Cognitive Maps for Applied Sciences and Engineering*, Papageorgiou EI (ed.). Springer: Berlin Heidelberg, Berlin, Heidelberg; 29–48.

Gray SA, Gray S, De Kok JL *et al*. 2015. Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. *Ecology and Society* **20**. https://doi.org/10.5751/ES-07396-200211

Groumpos PP. 2010. Fuzzy cognitive maps: basic theories and their application to complex systems. In *Fuzzy Cognitive Maps: Advances in Theory, Methodologies, Tools and Applications*, *Studies in Fuzziness and Soft Computing*, Glykas M (ed.). Springer: Berlin Heidelberg; 17–38.

Hewitt R, Escobar F. 2011. The territorial dynamics of fast-growing regions: unsustainable land use change and future policy challenges in Madrid, Spain. *Applied Geography* **31**: 650–667. https://doi.org/10.1016/j.apgeog.2010.11.002

Hobbs BF, Ludsin SA, Knight RL, Ryan PA, Biberhofer J, Ciborowski JJH. 2002. Fuzzy cognitive mapping as a tool to define management objectives for complex ecosystems. *Ecological Applications* **12**: 1548–1565. https://doi.org/10.1890/1051-0761(2002)012%5B1548:FCMAAT%5D2.0.CO;2

Isak KGQ, Wildenberg M, Adamescu CM, Skov F, De Blust G. 2009. Manual for applying fuzzy cognitive mapping—experiences from ALTER-Net. ALTER-Net: A Long-Term Biodiversity, Ecosystem and Awareness Research Network.

Jetter A. 2006. Elicitation—extracting knowledge from experts. In *Knowledge Integration. Physica-Verlag HD*, Jetter DA, Schröder PDH-H, Kraaijenbrink J, Wijnhoven PDF (eds.); 65–76 https://doi.org/10.1007/3-7908-1681-7_5

Jetter AJ, Kok K. 2014. Fuzzy cognitive maps for futures studies—a methodological assessment of concepts and methods. *Futures* **61**: 45–57. https://doi.org/10.1016/j.futures.2014.05.002

Kok K. 2009. The potential of fuzzy cognitive maps for semi-quantitative scenario development, with an example from Brazil. *Global Environmental Change* **19**: 122–133.

Kok K, Bärlund I, Flörke M *et al*. 2015. European participatory scenario development: strengthening the link between stories and models. *Climatic Change* **128**: 187–200. https://doi.org/10.1007/s10584-014-1143-y

Kosko B. 1986. Fuzzy cognitive maps. *International Journal of Man-Machine Studies* **24**: 65–75. https://doi.org/10.1016/S0020-7373(86)80040-2

Krugman P. 2013. The Excel depression. NewYork Times. http://www.nytimes.com/2013/04/19/opinion/krugman-the-excel-depression.html

Lang DJ, Wiek A, Bergmann M *et al*. 2012. Transdisciplinary research in sustainability science: practice, principles, and challenges. *Sustainability Science* **7**: 25–43. https://doi.org/10.1007/s11625-011-0149-x

Langfield-Smith K. 1992. Exploring the need for a shared cognitive map. *Journal of Management Studies* **29**: 349–368. https://doi.org/10.1111/j.1467-6486.1992.tb00669.x

MacCoun R, Perlmutter S. 2015. Blind analysis: hide results to seek the truth. *Nature* **526**: 187–189. https://doi.org/10.1038/526187a

McNutt M. 2014. Reproducibility. *Science* **343**: 229–229. https://doi.org/10.1126/science.1250475

Mehryar S, Sliuzas R, Sharifi A, Reckien D, van Maarseveen M. 2017. A structured participatory method to support policy option analysis in a social-ecological system. *Journal of Environmental Management* **197**: 360–372. https://doi.org/10.1016/j.jenvman.2017.04.017

Mezei J, Sarlin P. 2016. Aggregating expert knowledge for the measurement of systemic risk. *Decision Support Systems* **88**: 38–50. https://doi.org/10.1016/j.dss.2016.05.007

Miguel E, Camerer C, Casey K *et al*. 2014. Promoting transparency in social science research. *Science* **343**: 30–31. https://doi.org/10.1126/science.1245317

Mourhir A, Rachidi T, Papageorgiou EI, Karim M, Alaoui FS. 2016. A cognitive map framework to support integrated environmental assessment. *Environmental Modelling & Software* **77**: 81–94. https://doi.org/10.1016/j.envsoft.2015.11.018

Nuzzo R. 2015. How scientists fool themselves—and how they can stop. *Nature* **526**: 182–185. https://doi.org/10.1038/526182a

Obiedat M, Samarasinghe S. 2016. A novel semi-quantitative fuzzy cognitive map model for complexsystems for addressing challenging

DOI: 10.1002/sres.2519

participatory real life problems. *Applied Soft Computing* **48**: 91–110. https://doi.org/10.1016/j.asoc.2016.06.001
Olazabal M, Pascual U. 2016. Use of fuzzy cognitive maps to study urban resilience and transformation. *Environmental Innovation and Societal Transitions* **18**: 18–40. https://doi.org/10.1016/j.eist.2015.06.006
Olazabal M, Reckien D. 2015. Fuzzy cognitive mapping: applications to urban environmental decision-making. In *Handbook of Research Methods and Applications in Environmental Studies*, Ruth M (ed.). Edward Elgar Publishing; 576.
Olazabal M, Chiabai A, Foudi S, Neumann MB. 2018. Emergence of new knowledge for climate change adaptation. *Environmental Science & Policy* **83**: 46–53. https://doi.org/10.1016/j.envsci.2018.01.017
Özesmi U, Özesmi SL. 2004. Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling* **176**: 43–64. https://doi.org/10.1016/j.ecolmodel.2003.10.027
Papageorgiou EI, Salmeron JL. 2013. A review of fuzzy cognitive maps research during the last decade. *IEEE Transactions on Fuzzy Systems.* **21**: 66–79. https://doi.org/10.1109/TFUZZ.2012.2201727
Park KS, Kim SH. 1995. Fuzzy cognitive maps considering time relationships. *International Journal of Human-Computer Studies* **42**: 157–168. https://doi.org/10.1006/ijhc.1995.1007
Penn AS, Knight CJK, Lloyd DJB *et al*. 2013. Participatory development and analysis of a fuzzy cognitive map of the establishment of a bio-based economy in the Humber Region. *PLoS One* **8**: e78319. https://doi.org/10.1371/journal.pone.0078319
Reckien D. 2014. Weather extremes and street life in India—implications of fuzzy cognitive mapping as a new tool for semi-quantitative impact assessment and ranking of adaptation measures. *Global Environmental Change* **26**.
Reed MS. 2008. Stakeholder participation for environmental management: a literature review. *Biological Conservation* **141**: 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014
Russell JF. 2013. If a job is worth doing, it is worth doing twice. *Nature* **496**: 7–7. https://doi.org/10.1038/496007a
Tong A, Sainsbury P, Craig J. 2007. Consolidated criteria for reporting qualitative research (COREQ): a 32-item checklist for interviews and focus groups. *International Journal for Quality in Health Care* **19**: 349–357. https://doi.org/10.1093/intqhc/mzm042
Vanwindekens FM, Stilmant D, Baret PV. 2013. Development of a broadened cognitive mapping approach for analysing systems of practices in social-ecological systems. *Ecological Modelling* **250**: 352–362. https://doi.org/10.1016/j.ecolmodel.2012.11.023
Voinov A, Bousquet F. 2010. Modelling with stakeholders. *Environmental Modelling & Software* **25**: 1268–1281. https://doi.org/10.1016/j.envsoft.2010.03.007

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

DATA SM0: List of supplementary materials and brief description
DATA SM1: List of participating agents
DATA SM2: Interview guidelines
DATA SM3: Original data collected
DATA SM4: Notes taken during individual interviews
DATA SM5: Individual digitalised maps
DATA SM6: Adjacency matrices of individual maps
DATA SM7: Workbench for manipulation of original concepts
DATA SM8: Lists of concepts in the aggregated map and their meaning
DATA SM9: Individual adjacency matrices after Step 4
DATA SM10: R code for building the augmented matrix and collapsing
DATA SM11: Aggregated matrix
DATA SM12: Final aggregated map in NodeXL format

DOI: 10.1002/sres.2519