Environmental Science and Policy 83 (2018) 46–53

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Emergence of new knowledge for climate change adaptation

Marta Olazabal[a,*], Aline Chiabai[a], Sébastien Foudi[a], Marc B. Neumann[a,b]

[a] Basque Centre for Climate Change, BC3, 48940 Leioa, Spain
[b] IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain

ARTICLE INFO

Keywords:
Climate change adaptation
Knowledge co-production
Systems approach
Fuzzy cognitive mapping
Decision-making

ABSTRACT

Decision-making for climate change adaptation requires an integrated and cross-sectoral approach to adequately capture the complexity of interconnected systems. More meaningful decisions can be taken in an arena where different agents provide knowledge of specific domains. This paper uses a semi-quantitative method based on cognitive mapping to demonstrate how new knowledge emerges when combining knowledge from diverse agents. For the case of heatwaves in the city of Madrid (Spain) we elicit knowledge about climatic impacts across urban sectors and potential adaptation options. Knowledge is elicited in individual interviews and then aggregated using fuzzy cognitive maps. We observe that the individual maps vary considerably in size and structure and find evidence of diverse and even contradictory perceptions. There is no "super-stakeholder", who theoretically could provide full knowledge about mechanisms operating in this urban system: the maximum percentage of the final aggregated map explained by a single individual is 26% in terms of concepts and 13% in terms of connections. We illustrate how the emergence of new knowledge can be sustained by combining scientific and policy expertise. Our approach supports knowledge co-production and allows to account for the interconnectedness of urban sectors under climatic impacts in view of formulating more robust adaptation strategies.

1. Introduction

Knowledge co-production, understood as a collaborative process in which shared and usable knowledge (van Kerkhoff and Lebel, 2015) is produced out of a pool of diverse knowledge sources and types is fundamental for decision making in socio-ecological contexts and for the transition to global sustainability (Clark et al., 2016; van Kerkhoff and Lebel, 2015). Transdisciplinary approaches have been considered highly useful for addressing complexity, uncertainty and controversy (Serrao-Neumann et al., 2015). Although such approaches are not easy to implement (Hegger et al., 2012; Thompson et al., 2017) they have been found useful for integrating different knowledge domains for policy-making (McPhearson et al., 2016). Particularly in relation to climate change adaptation, methods that allow for collective learning are essential (Armitage et al., 2011; Borquez et al., 2017; Huitema et al., 2016; Lemos and Morehouse, 2005; Serrao-Neumann et al., 2015) to make systems more resilient, legitimate and effective (Howarth and Monasterolo, 2017; Huitema et al., 2016). Scholars have understood knowledge co-production about climate issues in a variety of ways (Bremer and Meisch, 2017); we use the concept here in the context of social learning, referring to a collaborative process in which scientists and all stakeholders including institutions jointly define a problem and its potential solutions by building system knowledge.

In this paper we particularly aim to show how knowledge can be co-produced through novel methodological approaches that help to analyse information in an integrated way. We present and apply a methodological approach that can facilitate and support knowledge co-production. Specifically, we show how to collect and combine different perspectives, to analyse pooled knowledge from different groups and to identify cross-sectoral synergies and interactions in view of supporting complex decision-making processes, such as those related to climate change adaptation. Through a case study in an urban context, we find evidence that combining diverse knowledge sources can support the emergence of new knowledge, which is expected to lead to a better understanding of climate change impacts and thus, to an improved basis for adaptation decision-making.

As climate change affects multiple sectors at multiple levels (Adger et al., 2005), effective adaptation planning requires taking into account diverse individual and collective perspectives (Bremer and Meisch, 2017; Collins and Ison, 2009; Grothmann and Patt, 2005) but also take into account potential barriers and mismatches that may arise (Wamsler, 2017). The ability to generate and use knowledge is one of

---

* Corresponding author at: Basque Centre for Climate Change, BC3, Edificio sede, Planta 1, Parque Científico UPV/EHU, Barrio Sarriena s/n, 48940 Leioa, Bizkaia, Spain.
E-mail addresses: marta.olazabal@bc3research.org (M. Olazabal), aline.chiabai@bc3research.org (A. Chiabai), sebastien.foudi@bc3research.org (S. Foudi), marc.neumann@bc3research.org (M.B. Neumann).

https://doi.org/10.1016/j.envsci.2018.01.017
Received 4 October 2017; Received in revised form 3 January 2018; Accepted 25 January 2018

the most important indicators of adaptive capacity (Williams et al., 2015), as rich and diverse knowledge is expected to improve the robustness of decisions. Eliciting knowledge that is scattered and disaggregated among diverse stakeholders is, however, a difficult task (Aylett, 2014). In some instances, knowledge is in the hands of groups or individuals with vested interests who are not inclined to share it. In others, they might simply not be aware of its value and therefore not perceive a need to share it. However, the use and combination of knowledge from many diverse sources is fundamental for effective adaptation decision-making, especially when data on the functioning and performance of a system is scarce or uncertain (Armitage et al., 2011; Mehryar et al., 2017; Olazabal and Reckien, 2015; Reckien, 2014).

The task of integrating different sources of knowledge is challenging. In the last decade, many scientists have emphasised the value of systems approaches for meeting the challenges of sustainable development and global environmental change and, in particular, climate change adaptation (Bai et al., 2016a,b; da Silva et al., 2012; Fiksel, 2006; Kelly, 1998). By ‘systems approach’ we mean characterising a system through a model that describes its central elements and how they are related to one another. The model can be built individually or collaboratively. Fig. 1 compares individual and combined perspectives, similar to the parable of the blind men and the elephant. In this parable (Shah, 1993), each man perceives one part of “the truth” by touching just one part of the animal, but the men are only able to “see” the reality when they combine their knowledge. Individual perspectives are valuable as the experiential knowledge of individuals can capture many details of specific parts of a system; combined perspectives, on the other hand, offer an integrated view, capable of better capturing the complexity of an entire system.

Eliciting and combining knowledge through a systems approach helps to understand how a system’s elements may interact. A systems approach for adaptation knowledge co-production is valuable to i) achieve a comprehensive understanding of how a complex system works, ii) discover cross-sectoral interactions and potential unintended impacts of adaptation decisions affecting infrastructures, services, resources and population, and iii) help identify the most efficient or effective ways of achieving certain adaptation goals. In this study, we address the first two of these; the third is beyond the scope of this work.

In this paper, we present quantifiable evidence of the value of a systems approach for knowledge co-production in climate change adaptation decision-making. Through a case study on heatwaves in an urban context, we show how using a procedure where knowledge from diverse social, institutional and scientific agents is brought together can support a broader understanding of climate change impacts and helps to build more robust system descriptions. In particular we study heatwave impacts in the city of Madrid (Spain) and potential adaptation options. For this, we use fuzzy cognitive mapping (FCM) (Jetter and Kok, 2014; Kosko, 1986; Özesmi and Özesmi, 2004; Papageorgiou, 2013) as a participatory, semi-quantitative expert-based approach useful for knowledge co-production. We collect individual perspectives (maps) on how a system performs under heatwaves in order to develop a combined map. We illustrate the potential value of the approach for knowledge co-production that can ultimately serve decision making for adaptation.

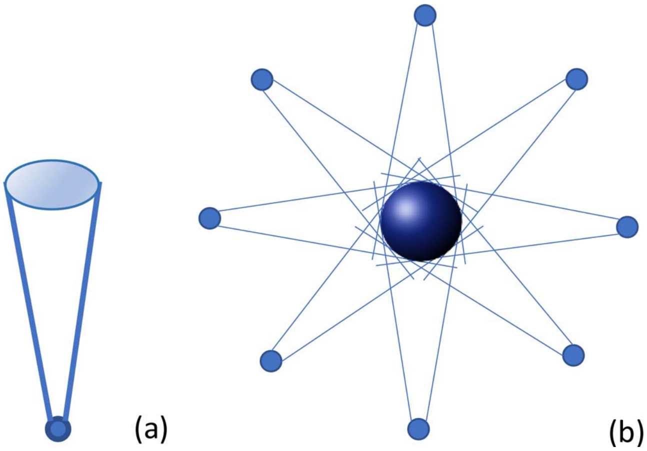

Fig. 1. Individual vs. combined perspectives. (a) Individual lens: contemplates knowledge from a single view point; (b) Multiple lenses: by combining different viewpoints an integrated, cross-sectoral and interdisciplinary perspective is obtained.

2. Methods and case study

In this paper, we conduct individual interviews with stakeholders in the city of Madrid to obtain cognitive maps. We compare these individual maps and then aggregate them. By analysing the aggregated map, we show how new knowledge emerges.

2.1. Fuzzy cognitive mapping (FCM)

FCM is a participatory, semi-quantitative method that allows the integration of views from different participants and construction of an aggregated model that can then be used to analyse scenarios (Jetter and Kok, 2014; Kosko, 1986; Özesmi and Özesmi, 2004). Participants develop maps consisting of concepts and weighted, directed connections. These causal maps reflect their experience, knowledge or perceptions about the system (see e.g. Gray et al., 2015; Olazabal and Pascual, 2016; Reckien, 2014). The mapping serves as a tool to collect disperse information and aggregate it into a model, which can then be used to identify interdependencies between concepts, including unexpected trade-offs and synergies. FCM can be applied at various stages of a decision-making cycle (Vogel et al., 2007). The methodological features involved in FCM make it a useful tool for knowledge co-production in systems characterised by complexity, uncertainty and scarcity of data (Mehryar et al., 2017; Olazabal and Reckien, 2015; Reckien, 2014).

A systems approach such as FCM, applied to climate change adaptation, allows to identify cascading effects and interactions across sectors that otherwise would be difficult to identify and analyse. This is what we refer to as new system knowledge and describe it as fragments of new understanding of the structure and behaviour of a system. When this new knowledge is obtained through the aggregation of individually elicited knowledge, it assists to overcome ignorance, misconceptions and biases of individual views (Kosko, 1992; Özesmi and Özesmi, 2004) and is therefore expected to be useful in adaptation decision-making processes.

2.2. Madrid heatwave case study

2.2.1. Objective

The case study that deals with the analysis of impacts and adaptation options in the context of heatwaves in the city of Madrid. To assess indirect impacts and design more robust adaptation measures, individual participants should cover different disciplines or sectors. We identify different knowledge sources and collect stakeholders’ perspectives on how different urban sectors (such as health, water, energy….) can be affected. These perspectives are then aggregated into a model and it is demonstrated how new knowledge emerges under scenario analysis.

2.2.2. Selecting stakeholders and knowledge domains

Stakeholders interviewed are experts from different fields and sectors that are directly or indirectly affected by heatwaves (health, climate change, urban planning and design, green infrastructures, …). By responding the two questions “What are the impacts of heatwaves in the city of Madrid?” and “What are the potential adaptation measures?”, participants were asked to describe the phenomena through a cognitive map and identify cause-effect relationships among the different elements in the system, as perceived by them (see Interview guidelines in SM1). We obtained 22 individual maps from 24 participants (including 2 groups of 2 participants that were used to working together). Participants selected were from: (i) different knowledge areas or sectors: health (41%), urban planning and design (18%), green and blue infrastructures (18%) and climate change (23%), and (ii) different professions: researchers (Rs, 46%) and decision-makers (DMs, 54%). The DMs (54%) were selected from different administrative levels of the public sector, local (23%), regional (13%) and national (12%), as well as from the health sector (8%).

2.2.3. *Elicitation and aggregation*

Maps are individually elicited from participants who identify the relevant concepts and cause-effect relationships between the concepts through directed graphs. In addition, they specify the sign (positive or negative) and assign weights between 0 and 1 indicating the strength of the relationships contained in their maps. In complex and new fields such as adaptation, expressing knowledge in 'vague' terms such as this one, represents an advantage that facilitates decision-making. The process is supervised and documented by an analyst, who then translates and digitalises the original maps, soliciting feedback from the participants if necessary. The original (digitalised) maps are available in SM2.

Individuals may i) express the same concepts with different words, ii) express different concepts with the same words, or iii) explain the same phenomena at different levels of detail. Therefore, to be able to combine (or aggregate) individual maps, these need to be normalised or 'homogenised'. 'Homogenisation' refers to the process of finding a common terminology and a common scale in order to unify the understanding of concepts and connections across individual maps. We propose to develop a workbench with detailed information on this process (SM3), providing transparency and allowing to revisit and modify the decisions taken in this crucial step at any time.

The individual homogenised maps are then aggregated into a single map (SM4). To capture connections that appear in more than one map, we suggest providing information on mean, standard deviation and coefficient of variation as well as to provide the number of maps in which the connection is active (see mean, sd, cv and count adjacency matrices in SM4).

2.2.4. *Analysis of individual maps (individual-lens approach)*

In this paper, first, we use an *individual-lens approach* (see Section 3.1) to analyse, compare and discuss the individual maps collected following the Fuzzy Cognitive Mapping (FCM) method. We first analyse and discuss the original maps as elicited during the interviews and then we analyse their similarity after they are homogenised (following the homogenisation step discussed above). The maps can be described using various characteristics, such as density D. D is represented by the fraction of connections that are active, i.e., the number of active connections divided by number of potential connections (Özesmi and Özesmi, 2004). To quantify similarity between maps, we use the Jaccard similarity coefficient (J), which is the ratio of intersection and union of concepts. For example, envisage map A with 10 concepts, map B with 12 concepts and A and B sharing 3 concepts then $J = 3/(12 + 10 - 3) = 0.158$. J provides information on how much new knowledge each participant provides and how much is shared. SM5 contains results of the characterisation and analysis of individual maps. The equations can be found in SM6.

2.2.5. *Analysis of aggregated map (combined-lens approach)*

Then, we use a *combined-lens approach* (see Section 3.2) to analyse the aggregated map and compare it to the individual homogenised maps. For this we again use the J and D indices. We additionally illustrate two effects: the effect of cascading impacts and the effect of cross-sectoral interdependencies in our resulting aggregated map. For the first one, we display up to third-order connections in a selection of concepts of the final aggregated map. For the second one, we analyse the cross-sectoral impacts of ecosystem-based adaptation measures.

FCM also allows to create sub-maps by grouping specific participants. In our case, we show the importance of considering both scientific and policy expertise in knowledge co-production processes. We compare two sub-group maps: one aggregating all decision-makers (DMs) and another all researchers (Rs). We compare the two maps with respect to D and assess their J.

2.2.6. *Scenario analysis and emergence of new knowledge*

A combined-lens approach facilitates the emergence of new co-produced knowledge. For this, we apply scenario analysis on the aggregated map. When performing scenario analysis in FCM, concepts can be manipulated in order to assess the impact of an action or a disturbance occurring in the system (see equation in SM6). In our case, we use scenario analysis to simulate how implementing an adaptation measure (green infrastructure deployment) impacts the system (see Section 3.3 and full results in SM8). To illustrate the potential of using this approach for knowledge co-production, we run the green infrastructure scenario also on the DM's and R's maps and compare their responses with those of the aggregated map.

3. Results and discussion

3.1. *Individual-lens approach*

3.1.1. *Elicited individual maps*

In this section we first present the results of analysing the elicited individual maps. Participants provide maps of different size and structure pointing towards very different underlying cognitions (Fig. 2 and SM2) and thus, towards a high diversity of knowledge. The density D is smaller for larger maps (see SM5). This decreasing density has previously been explained by the limited capacity of the human mind to perceive high numbers of connections between elements in a large system (Özesmi and Özesmi, 2004). One might expect that perceived complexity, reflected here with the number of concepts and connections, would vary with professional background. For example, it has been claimed that scientists normally contemplate issues in a more complex way (Funtowicz and Ravetz, 1995). We find some evidence of this in our experiment, where individual maps provided by Rs are on average slightly larger than individual maps provided by DMs. The number of concepts are $N_{DM} = 16.00 \pm 5.26$ and $N_R = 18.40 \pm 5.30$ and the number of connections are $N_{DM} = 20.08 \pm 8.86$ and $N_R = 24.60 \pm 8.15$ leading to similar average densities between the two groups ($D_{DM} = 0.0851 \pm 0.0214$; $D_R = 0.0823 \pm 0.0260$) (see SM5).

We observe that participants tend to provide more positive than negative relations (Fig. 2 and SM2, see for example Map#2, #10, #11, #12, #17), 72% of connections being positive. There is also evidence of contradictory perceptions. For example, 'Air Conditioning (AC)' is found to be both positively and negatively linked to 'Morbidity': some participants argued that AC decreases indoor temperatures and, thereby, decreases morbidity related to heat stress (i.e., a negative relation); others claimed that AC increases susceptibility to infections (in particular, the common cold) (i.e., a positive relation). Both perceptions are valid and meaningful and need to be taken into account for interpreting the results of adaptation scenarios. Another interesting point to consider is how agents assign weights to the connections. Participants express stronger connections more often than they do weaker ones, with 73% of connections having a weight higher than 0.5. This may be because participants are more inclined to recollect stronger cause-effect relations than weaker ones. Nevertheless, weaker relations can play a very important role in the propagation of impacts.

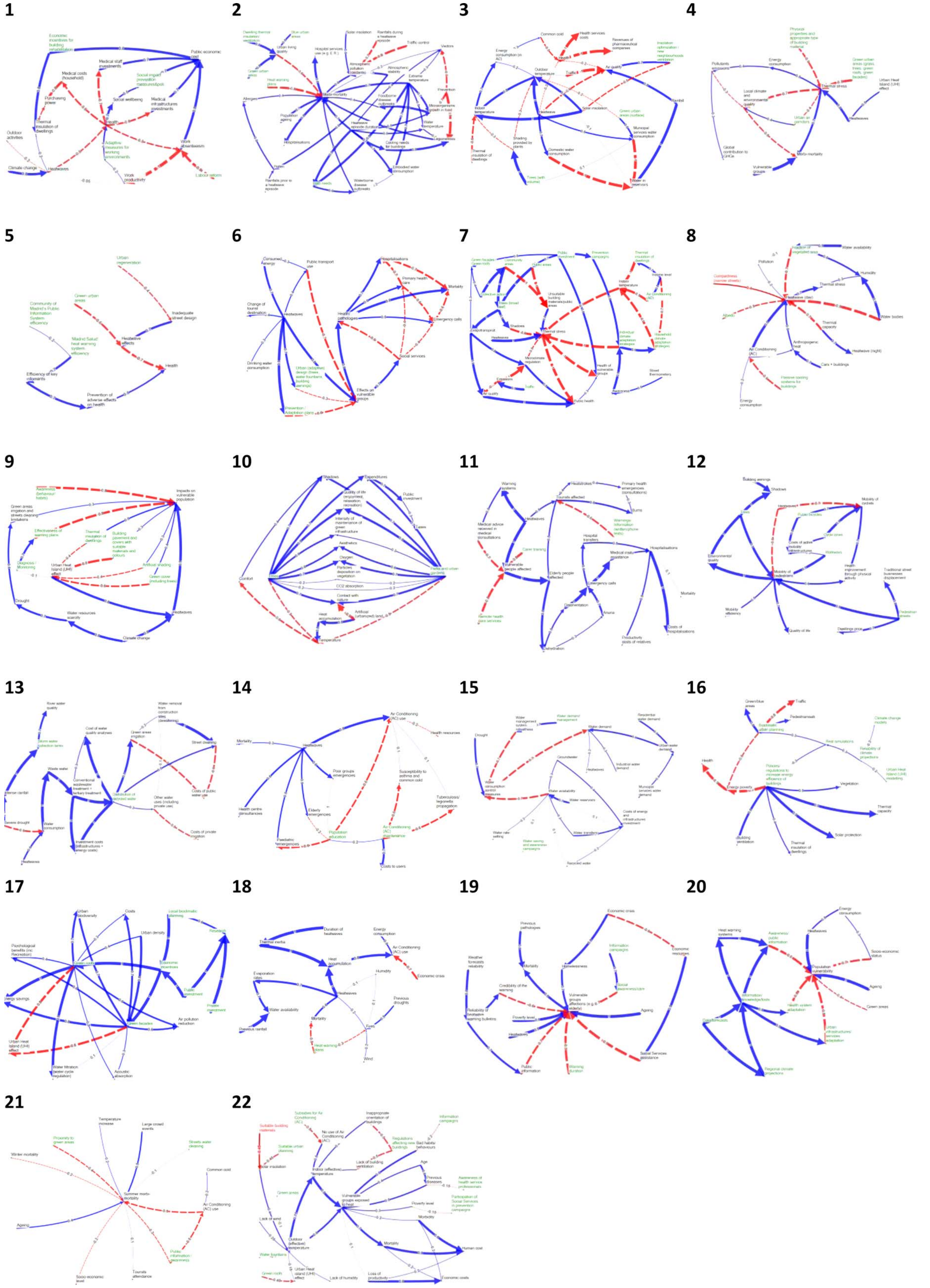

Fig. 2. Individual maps (before homogenization). Blue and red arrows represent positive and negative relations between concepts, respectively. Thickness of arrows reflects the strength of connections. Concepts in green refer to adaptation options. See SM2 for details on each of the elicited individual maps. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.1.2. Individual maps after homogenisation

After the process of homogenisation (see Section 2.2.3.), the 380 concepts contained in the 22 original maps are reduced to 291 and the 491 connections to 394 (see data in SM5 and homogenisation process applied in SM3). We evaluate the similarity between the homogenised individual maps using the Jaccard similarity index *J*. Note, however, that a high J does not necessarily mean that participants perceive the cause-effect relations in the same way. For example, although participants #19 and #20 (both from urban planning and design) provide maps with the highest similarity (J = 0.43), they only share two out of 28 connections (see SM5). That is, although individuals may identify the same concepts, they may connect them in very different ways. Therefore, we also analyse the similarity between maps in terms of shared connections. We find that, out of the 394 active connections in individual homogenised maps, 59% (233) are mentioned only once (see SM5). This means that almost two-thirds of the information related to how concepts are connected with each other is unique, i.e. provided by just one of the participants. We analyse the distribution of how connections are duplicated across maps and find that there are only two connections that appear across five maps (see SM5). From these results, we conclude that considering a diversity of individual sources is critical for gaining rich and detailed system knowledge. Our results show that considering different knowledge sources allows connecting ideas (i.e. concepts) and produces system knowledge closer to reality. As we show in the following section, this can help us to understand complex phenomena and identify "hidden" (indirect) connections.

3.2. Combined-lens approach

Using the combined-lens approach allows us to contemplate multiple perspectives and facilitates co-production of knowledge (Fig. 1). In order to achieve this, the individual homogenised maps are aggregated. As explained in Section 2, we analyse the aggregated map and two sub-maps (Rs' and DMs' maps) to additionally discuss how science and policy can be combined to achieve a better understanding of the system.

First of all, as a result of comparing individual maps and the final aggregated map, i.e. individual knowledge sources against the result of their combination, we conclude that there is no "super-stakeholder", who theoretically could provide full knowledge about the mechanisms governing phenomena in the system, namely, heatwaves in the city of Madrid. In terms of concepts, the maximum percentage of the final aggregated map explained by a single individual is 26% and in terms of connections only 13% (see SM5, percentage of concepts and connections in final aggregated map; Table SM5.1). The resulting combined map consists of 87 concepts and 295 connections, including 13 self-loops (see SM4). As the number of potential connections is 7569 (87*87) the density of the aggregated final map is D = 0.0377.

We display up to third-order connections for selected concepts (Fig. 3). With some exceptions (see, e.g., "heatwaves (night)") the higher-order connections become difficult to keep track of through human perception alone. For climate impact assessment, however, analysis of chains of influence and interdependencies is critical to uncover indirect consequences across scales and sectors (Dawson, 2015). Adaptation options assessment requires analysis of cascading impacts to prevent as far as possible unintended consequences, including maladaptation (Barnett and O'Neill, 2010; Juhola et al., 2016). A systems approach such as the one presented here is useful in this regard, as it can be used to compute cascading interactions.

Through an example of ecosystem-based adaptation measures (see Fig. 4), we illustrate cross-sectoral interdependencies in our resulting aggregated map. In our study, "green infrastructures" (e.g., urban trees and parks) and "blue infrastructures' (e.g., lakes and water fountains) were mentioned by many participants as important elements to reduce heatwave impacts in urban areas. As perceived by participants, the most important direct benefits (first-order connections) of green and blue infrastructures in Madrid are related to 'climate and environment' and 'urban planning, management and design'. Additionally, green and blue infrastructures are perceived to significantly reduce energy consumption and thermal stress. The final map enables a learning process about the importance of green and blue infrastructures across sectors. As perceived by the stakeholders, they do not only exhibit a positive influence on the environment and quality of life, but may also produce negative impacts on the economy (costs arising from maintenance) and on health (in particular, allergies) (Dobbs et al., 2014; Escobedo et al., 2011; Gomez-Baggethun and Barton, 2013; Roy et al., 2012; Villa et al., 2014).

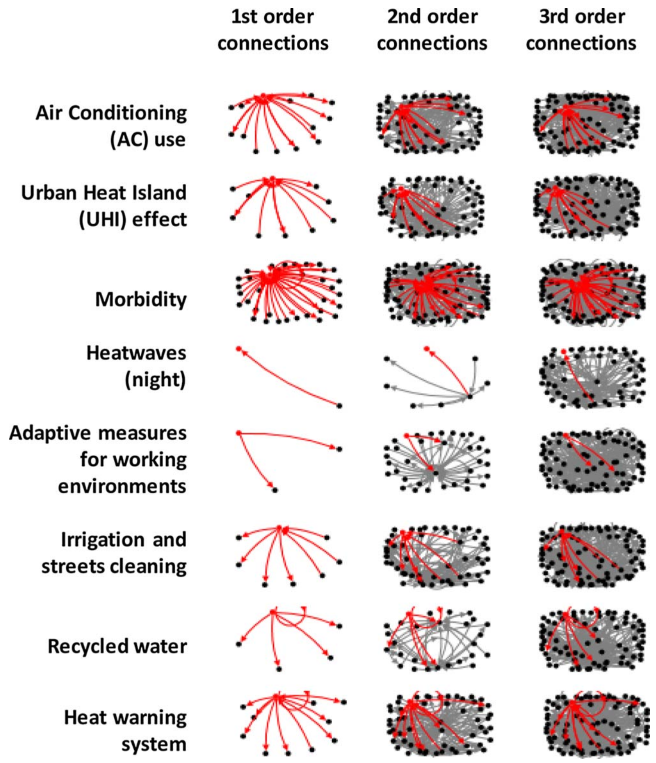

Fig. 3. Levels of adjacent concepts illustrated through first-, second- and third-order connections. The red dot denotes the concept analyzed (indicated in the far-left column). The red connections reflect the first level of adjacent concepts (first-order connections). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We divide the final aggregated map into two maps: one containing the maps of the 10 Rs and one containing the maps of the 12 DMs. The R map (density = 0.0401, 65 concepts and 175 connections) and the DM map (density = 0.0430, 60 concepts and 160 connections) show similar complexity. In terms of Jaccard similarity, we find that the R map explains 75% of the final map whereas the DM map explains 69%. The fact that neither of the groups are able to explain the entire final map highlights the relevance of knowledge co-production between science and policy domains.

3.3. Emergence of new knowledge for adaptation

The combination of individual sources of knowledge alone does not guarantee the emergence of new co-produced knowledge. The final product (the aggregated map in our case) needs to be used for decision-making to allow the production of previously unknown knowledge on the system. To this end, FCM allows building scenarios of possible futures. As an illustration, we simulate and discuss the impacts of increasing urban green infrastructures. We quantify the relative change from a low to a high deployment scenario (Table 1, full results in SM8). In order to find evidence on the production of new knowledge for climate change adaptation, we show the impacts on the aggregated

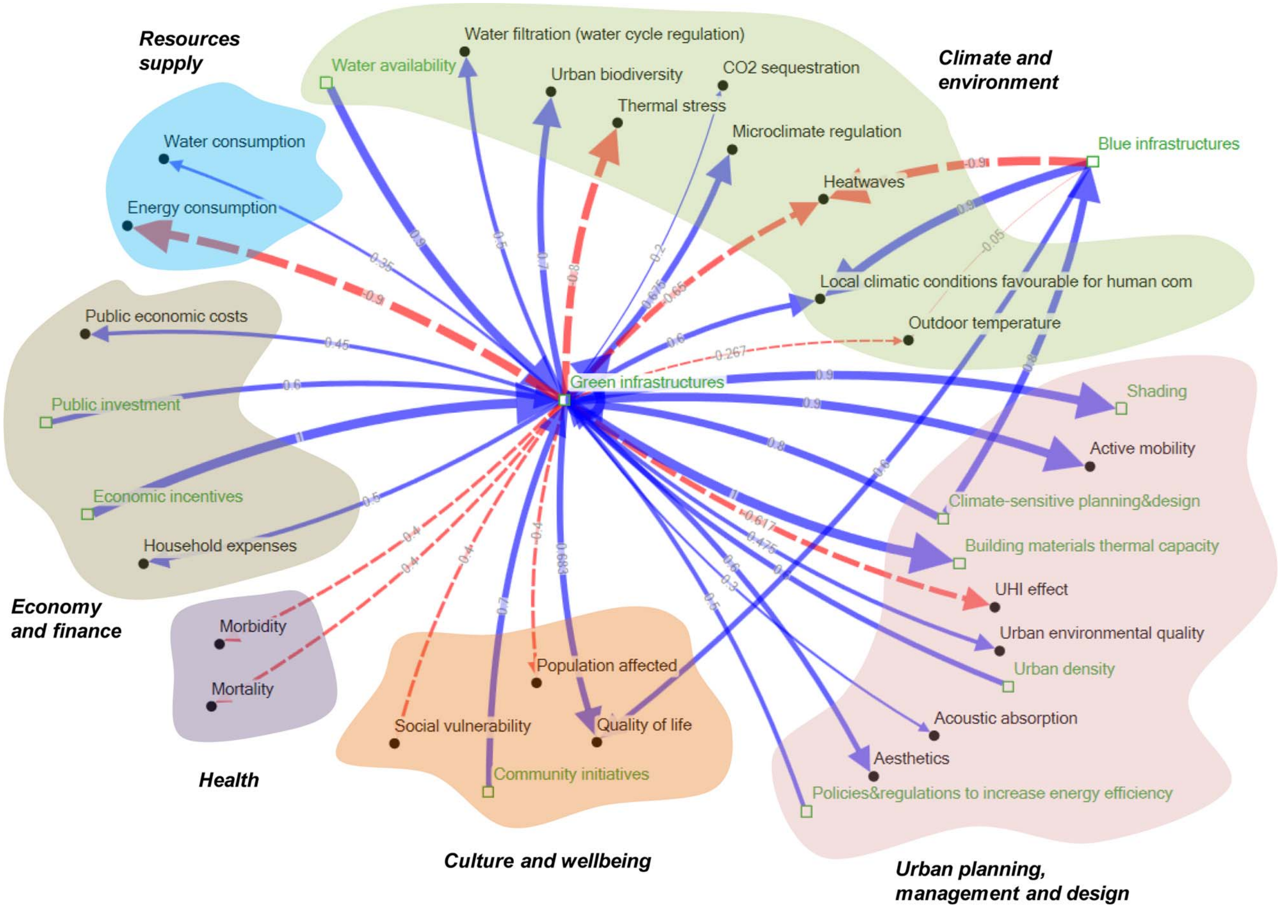

Fig. 4. Positive (blue-solid arrows) and negative (red-dashed arrows) effects of green and blue infrastructures in the city of Madrid (first-order connections). Arrow thickness depicts the relative importance of the causal effect. Shaded areas reflect different urban sectors. Concepts in green refer to adaptation options identified by participants. See SM7 for a higher resolution figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1

Scenario analysis for green infrastructure deployment. (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article.).

Id	Concepts	AGGR.	DM	R
4	Active mobility	🟩 14.48%	🟩 24.04%	0.00%
22	Energy consumption	🟥 -30.66%	0.06%	🟥 -29.47%
30	Heatwaves	🟥 -55.22%	🟥 -15.88%	🟥 -47.13%
40	Microclimate regulation	🟩 21.93%	🟩 8.38%	🟩 33.41%
69	Thermal stress	🟥 -63.02%	0.00%	🟥 -64.15%
78	Water consumption	🟩 7.90%	🟥 -3.00%	🟩 6.49%

Legend: Aggr. = final aggregated map; DM = decision-maker map (see SM8); R = researcher map. Red: negative impact, Green: positive impact.

(Aggr.) map, the DM map and the R map (see Table 1). This comparison shows that considering the combination of knowledge sources can sometimes lead to radically different system behaviour.

In general, the sign of impacts (positive: green, or negative: red) is the same across the three maps (Aggr., DM and R); however, there are exceptions worth exploring that show us the value of the combined-lens approach. For example, the DM map does not identify certain impacts which are identified by the R map, e.g., the impact of green infrastructure deployment on 'energy consumption' (Id. 22, Table 1) or on 'thermal stress' (Id. 69). In other cases, information provided by DMs and Rs is different. For example, results for the R map show that 'water consumption' (Id. 78) increases with increasing green infrastructure deployment, due to a greater need for irrigation, whereas the DM map reveals a cascading effect resulting from the regulation of outdoor temperature which reduces the impact of heatwaves which in turn leads to a lower consumption of water. Both refer to existing phenomena that need to be taken into account (see Aggr. column, Table 1) to an adequate planning of adaptive measures.

New knowledge emerges when analysing the combined map through scenario building. For example, according to the DM map, an increase of green infrastructures would reduce the impact of a heatwave by 15% (Id. 30), whereas the R map points to a stronger reduction of 47%. Interestingly, the combination of the two maps does not result in an averaging of the two but in an even stronger reduction of 55%. This illustrates an example of how new knowledge can emerge. Other cases that are evidence of an emergence of new knowledge are the impact of heatwaves on active mobility (Id. 4) and microclimate regulation (Id. 40), see Table 1. These examples result from cascading and cross-sectoral impacts which are only captured through a combined-lens approach and their implications only perceived through scenario analysis.

4. Conclusions

Preparing systems to successfully adapt to climate change requires a deep understanding of their complex structure and functioning. Knowledge co-production helps to acquire this understanding through a collaborative process in which knowledge of diverse sources is put together to build an integrated view of the system. Knowledge co-production acts as a trigger for learning which is a critical aspect of the adaptive capacity of a society. However, combining different types of knowledge and producing new forms of it, is not a simple task. For this reason, exploring and using new tools and approaches that facilitate knowledge co-production is essential to strengthen adaptation decision-making.

In this paper, we test a semi-quantitative participatory method to facilitate knowledge co-production in the context of climate change adaptation. Through a case study on heatwaves in the city of Madrid (Spain), we use Fuzzy Cognitive Mapping (FCM) as a systems approach to combine individual sources of knowledge in order to support the production of a holistic understanding of the behaviour of the system under climatic impacts.

We combine knowledge and experiences from a wide range of key stakeholders from science and policy in the form of individual cognitive maps. As a signal of the diversity of sources selected, we found considerable variation in individual maps' size and structure, with a limited number of shared concepts and connections across maps. We show how aggregating the individual maps and then running scenario analysis on the final map, enables the emergence of new knowledge. Our results show how a shared view of the system can help to identify cause-effect pathways between subsystems and thus may uncover potentially unexpected feedbacks. We learn how such knowledge could have never been gained through individual system perspectives alone. We additionally illustrate how researchers and decision-makers knowledge can be complementary. We conclude that new knowledge co-produced through a participatory systems approach such as the one tested here, is expected to improve robustness of decision-making and enhance social learning processes for adaptation.

Authors' contributions

M.O., M.B.N. and A.C. designed the experiment. M.O. led the study with support of M.B.N. M.O. performed elicitation, pre-processing and homogenisation as well as analysis of individual and aggregate maps. All authors jointly discussed the results and the Supplementary material.

Acknowledgements

This study is part of the Bottom-up climate adaptation strategies for a sustainable Europe (BASE) project funded by the European Union's Seventh Framework Programme for research, technological development and demonstration activities under Grant Agreement No. 308337. MO (FPDI-2013-16631) and MBN (RYC-2013-13628) acknowledge co-funding from the Spanish Ministry of Economy and Competitiveness (MINECO). The authors would like to thank Ana Iglesias, Luis Garrote and Pedro Iglesias from the Universidad Politécnica de Madrid (UPM) for their support in establishing contacts with the participants in this study. The authors are grateful to the 24 participants who devoted their time and shared their knowledge. The authors would also like to thank Sérgio H. Faria and Bosco Lliso for their suggestions on a final version of the manuscript and Ignacio Palomo for drawing the analogy between the study and the ancient parable of the blind men and the elephant.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2018.01.017.

References

Adger, W.N., Arnell, N.W., Tompkins, E.L., 2005. Successful adaptation to climate change across scales. Glob. Environ. Change Part A 15, 77–86.

Armitage, D., Berkes, F., Dale, A., Kocho-Schellenberg, E., Patton, E., 2011. Co-management and the co-production of knowledge: learning to adapt in Canada's Arctic. Glob. Environ. Change 21, 995–1004. http://dx.doi.org/10.1016/j.gloenvcha.2011.04.006.

Aylett, A., 2014. Progress and Challenges in the Urban Governance of Climate Change: Results of a Global Survey. MIT, Cambridge, MA.

Bai, X., Surveyer, A., Elmqvist, T., Gatzweiler, F.W., Güneralp, B., Parnell, S., Prieur-Richard, A.-H., Shrivastava, P., Siri, J.G., Stafford-Smith, M., Toussaint, J.-P., Webb, R., 2016a. Defining and advancing a systems approach for sustainable cities. Curr. Opin. Environ. Sustain. Open Issue Part I 23, 69–78. http://dx.doi.org/10.1016/j.cosust.2016.11.010.

Bai, X., van der Leeuw, S., O'Brien, K., Berkhout, F., Biermann, F., Brondizio, E.S., Cudennec, C., Dearing, J., Duraiappah, A., Glaser, M., Revkin, A., Steffen, W., Syvitski, J., 2016b. Plausible and desirable futures in the Anthropocene: a new research agenda. Glob. Environ. Change. http://dx.doi.org/10.1016/j.gloenvcha.2015.09.017.

Barnett, J., O'Neill, S., 2010. Maladaptation. Glob. Environ. Change 20, 211–213.

Borquez, R., Aldunce, P., Adler, C., 2017. Resilience to climate change: from theory to practice through co-production of knowledge in Chile. Sustain. Sci. 12, 163–176. http://dx.doi.org/10.1007/s11625-016-0400-6.

Bremer, S., Meisch, S., 2017. Co-production in climate change research: reviewing different perspectives. WIRES Clim. Change 8, e482. http://dx.doi.org/10.1002/wcc.482.

Clark, W.C., van Kerkhoff, L., Lebel, L., Gallopin, G.C., 2016. Crafting usable knowledge for sustainable development. PNAS 113, 4570–4578. http://dx.doi.org/10.1073/pnas.1601266113.

Collins, K., Ison, R., 2009. Jumping off Arnstein's ladder: social learning as a new policy paradigm for climate change adaptation. Env. Pol. Gov. 19, 358–373. http://dx.doi.org/10.1002/eet.523.

Dawson, R.J., 2015. Handling interdependencies in climate change risk assessment. Climate 3, 1079–1096. http://dx.doi.org/10.3390/cli3041079.

da Silva, J., Kernaghan, S., Luque, A., 2012. A systems approach to meeting the challenges of urban climate change. Int. J. Urban Sustain. Dev. 4, 125–145. http://dx.doi.org/10.1080/19463138.2012.718279.

Dobbs, C., Kendal, D., Nitschke, C.R., 2014. Multiple ecosystem services and disservices of the urban forest establishing their connections with landscape structure and socio-demographics. Ecol. Indic. 43, 44–55. http://dx.doi.org/10.1016/j.ecolind.2014.02.007.

Escobedo, F.J., Kroeger, T., Wagner, J.E., 2011. Urban forests and pollution mitigation: analyzing ecosystem services and disservices. Environ. Pollut. 159, 2078–2087.

Fiksel, J., 2006. Sustainability and resilience: toward a systems approach. Sustain.: Sci. Pract. Policy 2.

Funtowicz, S.O., Ravetz, J.R., 1995. Science for the post normal age. In: Westra, L., Lemons, J. (Eds.), Perspectives on Ecological Integrity. Springer, Netherlands, pp. 146–161.

Gomez-Baggethun, E., Barton, D.N., 2013. Classifying and valuing ecosystem services for urban planning. Ecol. Econ. 86, 235–245. http://dx.doi.org/10.1016/j.ecolecon.2012.08.019.

Gray, S.A., Gray, S., De Kok, J.L., Helfgott, A.E.R., O'Dwyer, B., Jordan, R., Nyaki, A., 2015. Using fuzzy cognitive mapping as a participatory approach to analyze change, preferred states, and perceived resilience of social-ecological systems. Ecol. Soc. 20. http://dx.doi.org/10.5751/ES-07396-200211.

Grothmann, T., Patt, A., 2005. Adaptive capacity and human cognition: the process of individual adaptation to climate change. Glob. Environ. Change 15, 199–213. http://dx.doi.org/10.1016/j.gloenvcha.2005.01.002.

Hegger, D., Lamers, M., Van Zeijl-Rozema, A., Dieperink, C., 2012. Conceptualising joint knowledge production in regional climate change adaptation projects: success conditions and levers for action. Environ. Sci. Policy 18, 52–65. http://dx.doi.org/10.1016/j.envsci.2012.01.002.

Howarth, C., Monasterolo, I., 2017. Opportunities for knowledge co-production across the energy-food-water nexus: making interdisciplinary approaches work for better climate decision making. Environ. Sci. Policy 75, 103–110. http://dx.doi.org/10.1016/j.envsci.2017.05.019.

Huitema, D., Adger, W.N., Berkhout, F., Massey, E., Mazmanian, D., Munaretto, S., Plummer, R., Termeer, C.C.J.A.M., 2016. The governance of adaptation: choices, reasons, and effects. Introduction to the Special Feature. Ecol. Soc. 21. http://dx.doi.org/10.5751/ES-08797-210337.

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

Juhola, S., Glaas, E., Linnér, B.-O., Neset, T.-S., 2016. Redefining maladaptation. Environ. Sci. Policy 55 (Part 1), 135–140. http://dx.doi.org/10.1016/j.envsci.2015.09.014.

Kelly, K.L., 1998. A systems approach to identifying decisive information for sustainable development. Eur. J. Oper. Res. 109, 452–464. http://dx.doi.org/10.1016/s0377-2217(98)00070-8.

Kosko, B., 1986. Fuzzy cognitive maps. Int. J. Man Mach. Stud. 24, 65–75. http://dx.doi.org/10.1016/S0020-7373(86)80040-2.

Kosko, B., 1992. Neural Networks and Fuzzy Systems: A Dynamical Systems Approach to Machine Intelligence. Prentice-Hall, Inc., Upper Saddle River, NJ, USA.

Lemos, M.C., Morehouse, B.J., 2005. The co-production of science and policy in integrated climate assessments. Glob. Environ. Change 15, 57–68. http://dx.doi.org/10.1016/j.gloenvcha.2004.09.004.

McPhearson, T., Parnell, S., Simon, D., Gaffney, O., Elmqvist, T., Bai, X., Roberts, D., Revi, A., 2016. Scientists must have a say in the future of cities. Nat. News 538, 165. http://dx.doi.org/10.1038/538165a.

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. J. Environ. Manage. 197, 360–372. http://dx.doi.org/10.1016/j.jenvman.2017.04.017.

Olazabal, M., Pascual, U., 2016. Use of fuzzy cognitive maps to study urban resilience and transformation. Environ. Innov. Soc. Transit. 18, 18–40. http://dx.doi.org/10.1016/j.eist.2015.06.006.

Olazabal, M., Reckien, D., 2015. Fuzzy Cognitive Mapping: applications to urban environmental decision-making. In: Ruth, M. (Ed.), Handbook of Research Methods and Applications in Environmental Studies. Edward Elgar Publishing p. 576.

Özesmi, U., Özesmi, S.L., 2004. Ecological models based on people's knowledge: a multistep fuzzy cognitive mapping approach. Ecol. Modell. 176, 43–64. http://dx.doi.org/10.1016/j.ecolmodel.2003.10.027.

Papageorgiou, E.I., 2013. Review study on fuzzy cognitive maps and their applications during the last decade. In: Glykas, M. (Ed.), Business Process Management, Studies in Computational Intelligence. Springer, Berlin Heidelberg, pp. 281–298.

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. Glob. Environ. Change 26.

Roy, S., Byrne, J., Pickering, C., 2012. A systematic quantitative review of urban tree benefits, costs, and assessment methods across cities in different climatic zones. Urban For. Urban Greening 11, 351–363.

Serrao-Neumann, S., Schuch, G., Harman, B., Crick, F., Sano, M., Sahin, O., van Staden, R., Baum, S., Low Choy, D., 2015. One human settlement: a transdisciplinary approach to climate change adaptation research. Futures 'Adv. Transdiscip. 2004–2014' 65, 97–109. http://dx.doi.org/10.1016/j.futures.2014.08.011.

Shah, I., 1993. Tales of the Dervishes: Teaching Stories of the Sufi Masters over the Past Thousand Years. Arkana, New York.

Thompson, M.A., Owen, S., Lindsay, J.M., Leonard, G.S., Cronin, S.J., 2017. Scientist and stakeholder perspectives of transdisciplinary research: early attitudes, expectations, and tensions. Environ. Sci. Policy 74, 30–39. http://dx.doi.org/10.1016/j.envsci.2017.04.006.

van Kerkhoff, L., Lebel, L., 2015. Coproductive capacities: rethinking science-governance relations in a diverse world. Ecol. Soc. 20. http://dx.doi.org/10.5751/ES-07188-200114.

Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Athanasiadis, I.N., Balbi, S., 2014. The misconception of ecosystem disservices: how a catchy term may yield the wrong messages for science and society. Ecosyst. Serv. 10, 52–53. http://dx.doi.org/10.1016/j.ecoser.2014.09.003.

Vogel, C., Moser, S.C., Kasperson, R.E., Dabelko, G.D., 2007. Linking vulnerability, adaptation, and resilience science to practice: pathways, players, and partnerships. Glob. Environ. Change 17, 349–364.

Wamsler, C., 2017. Stakeholder involvement in strategic adaptation planning: transdisciplinarity and co-production at stake? Environ. Sci. Policy 75, 148–157. http://dx.doi.org/10.1016/j.envsci.2017.03.016.

Williams, C., Fenton, A., Huq, S., 2015. Knowledge and adaptive capacity. Nat. Clim. Change 5, 82–83. http://dx.doi.org/10.1038/nclimate2476.

Dr. Marta Olazabal is research fellow at the Basque Centre for Climate Change (BC3). She has a background on Environmental Engineering (Bsc 2004, MSc 2009, School of Engineering of Bilbao) and a PhD on Land Economy (University of Cambridge, 2015). She has been recipient of several individual fellowships that have allowed her to undertake international scientific stays in Germany, The Netherlands, UK and Canada. In 2011, she co-founded the Urban Resilience Research Network (URNet). She is interested in urban sustainability, climate change governance and systems thinking.

Dr. Aline Chiabai is Research Professor at BC3 (Basque Centre for Climate Change) where she leads the research line on health and climate. She has a PhD in Transport, Traffic and Environment, a Master in Environmental Quality Management, and has developed an expertise in environmental and health economics. Her research interests include the assessment of climate impacts on health, combined with other environmental stressors, the evaluation of adaptation strategies for policy guidance with a multi-sectoral perspective, using health-related assessment methods and indicators. Recent work includes the role played by healthier and more sustainable lifestyles to increase population resilience.

Dr Sebastien Foudi is a post-doctoral fellow at the Basque Centre for Climate Change (BC3). He holds a PhD in Economic from the University of Toulouse (France). His research focuses on the contributions of economics to risk assessment and risk management. His work contributed in the domains of agriculture, biodiversity, floods, and green infrastructures.

Dr. Marc Neumann is Ikerbasque Research Professor at the Basque Centre for Climate Change. He holds a PhD in Environmental Engineering from ETH Zurich. Current work focuses on the treatment of uncertainty for climate change adaptation and mitigation. He is especially interested in exploring transdisciplinary approaches to environmental modelling that address the complexity arising from co-emergent physical- and social phenomena.