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Measuring knowledge and action changes in the light of urban climate resilience

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ABSTRACT

Climate resilience has gained an essential role in research as well as in international policies. An increasing number of cities are adapting to climate change to enhance their climate resilience. Given the complexity of urban systems in combination with the acceleration of climate and social change, it is challenging to measure the success of resilience-rising activities. To manage and accelerate the learning process and the transformation process, monitoring and evaluation of implemented adaptation measures are crucial. Most of the currently used indicator sets are dealing with system-focused changes. However, actor-focused changes are less addressed in holistic indicator sets, even if individual agency assumes an important role in the transformation process. This research was intended to design a framework for individual climate resilience agency and operationalise it in a composite indicator set. The indicator set is implemented in a survey with 14 research projects in Germany. Finally, the indicator set is verified using statistical and empirical validation. The study presents an applicable indicator set, which reveals more in-depth insights into the individual climate resilience agency and changes within adaptation measurements. Further, the set can be applied in both one-time assessments and repetitive measurement. Therefore, the tool can be implemented as a monitoring tool, as well as a formative evaluation tool, in the climate resilience adaptation context.

1. Introduction

Nine of the last 20 years rank among the ten warmest since measurements began [50]. The frequency and intensity of climate change-related extreme events have increased over the last decades [31] and their number will continue to rise in the future. Furthermore, global trends such as urbanisation, increasing population, or the acceleration of social change, are forcing uncertainties as well. Against this background, resilience has become an essential concept in various disciplines – e.g. spatial planning, geography, governance or disaster management [12,17], [40, 72,73].

Besides research, resilience has also received an essential role in international policies and agreements, for example, U.N. Habitat III, Sustainable Development Goals (SDG), UNFCCC Paris Agreement, Sendai Framework for Disaster Risk Reduction, to name a few [72,73]. However, cities and communities need to transfer the concept of resilience into dedicated actions as their potential for implementing behavioural, economic and technological transformations is widely recognised [33]. City networks such as the 100 Resilient Cities foundation, C40 or ICLEI support the process of building urban resilience [72].

To build urban resilience, monitoring and evaluation of implemented adaptation measures are crucial. It is challenging to map resilience enhancing activities' success as cities need to be considered as complex and multi-faceted systems [20]. Accordingly, due to accelerating climate and social change [42,60] and rising uncertainty, dynamics, risks, and a vast amount of simultaneity [43], monitoring and evaluation of adaptation-activities became even more critical [49,60]. In order to support, govern and steer a fast transformation process, information about the effects of such measurements is needed. On the short term, these effects are not visible within indicators measuring resilience for the entire urban system, considering all the different sub-systems, due to the difference of scales. Hence, an interdisciplinary cross-referential approach is needed to monitor and evaluate adaptation measures. This paper differentiates between "system-based" approaches measuring the entire system (e.g. urban, community) and measuring the effects of adaptation measures on actors (actor-based).

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Most resilience indicator sets focus on quantifiable ecological, economic, and socio-economic data [3,15,14,66,73]. They assess on county (e.g. [14,21]), city (e.g. [65]), community (e.g. [59]), neighbourhood [57] or household [35,68] level [81,82]. Some frameworks apply an integrated approach by using qualitative methods both during framework development (mostly) and for assessment [79,35]. Some approaches, for example, the embrace framework of [38], address action and learning of communities, yet primarily on the system level. Eventually, only actors can perform the transformation into a resilient urban system [4].

Enhancing resilience is closely interwined with every citizen's individual agency [52,55]. Although place-based community resilience has been mainstreamed already, the individual scale is less addressed [55]. The existing resilience or disaster risk indicator sets on an individual - or household-specific - scale are applying the sustainable livelihood approach [6;11;25,34,71] or adaptive capacity [41] for measurement. These tend to focus on livelihood, social or community resilience [63,58]. Besides these measurement frameworks, a diverse range of approaches which focus on subjective resilience exists [7]. Though, the importance of measuring soft and actor-focused factors of improving the urban climate resilience – e.g. knowledge, behaviour, motivation, agency – are pointed out in different studies but addressed less actively in the evaluation and monitoring context [11,13;78].

The research project MONARES (monitoring adaptation measures and climate resilience in cities), funded by the German Federal Ministry of Education and Research (BMBF) between 2017 and 2020, integrated both perspectives, system-focused and actor-focused. We developed an inclusive approach for measuring and evaluating climate change adaptation measurements (Fig. 1). A climate resilience indicator set focusing on the urban system and long-term changes was developed (see [20,46]). Furthermore, we designed a guideline to evaluate and monitor climate resilience-enhancing adaptation measures [36]. In the following, the actor-based approach is described more in detail.

Our main objective is to monitor and evaluate individual climate resilience agency. We achieve this by 1. developing a framework for individual climate resilience agency; 2. operationalising the framework in a composite indicator set including individual indicators and indicator questions; 3. implementing the approach into a survey tool and surveying within MONARES in 2019 and 2020; 4. validating, both statistically and empirically, the framework as well as the tool. To achieve these objectives, we answer the following research questions:

1) How can the actor-related impact goals “changes in knowledge and action” be deconstructed and transferred into a measurement framework for individual climate resilience agency?
2) How to operationalise, measure and quantify the developed dimensions with specific indicators?
3) What changes in the preconditions of individual climate resilience agency have been detected during the timespan of one year?
4) How robust are the framework and its dimensions, including the indicators, in measuring individual climate resilience agency preconditions?

The next section introduces the MONARES project and gives theoretical aspects regarding climate resilience and knowledge. In Section 3, we provide the individual climate resilience agency (ICRA) framework and further details on the study sample as well as statistical methods applied. In Section 4, we discuss important aspects of the validation and temporal changes measured. In the last section, we conclude by summarising the main results and answering the research questions.

2. Theoretical and conceptual background

2.1. MONARES – Case study

The research project MONARES, funded by the German Federal Ministry of Education and Research, focuses on (1) developing a consistent understanding of resilience for both practitioners and academia, (2) shaping the adaptation and transformation process into a transparent process of governing and steering as well as (3) the use of resilience and adaptation measurements [20]. MONARES, as a cross-sectional project, is collaborating with 14 other projects of the funding initiative ‘Climate resilience through action in cities and regions’ of the BMBF. These interdisciplinary projects are focusing on enhancing urban climate resilience through adaptation measures [20]. As these projects conduct local research in 33 different municipalities throughout Germany, they differ regarding the following parameters:

- focused weather hazard (heat, drought, severe precipitation events, flooding, storm)
- scale (district, city, suburb, region)
- adaptation measurement focus (e.g. infrastructure, planning, green infrastructure, capacity building, governance)

MONARES followed a co-creational, integrative mixed-methods approach to develop a resilience framework [47] with five dimensions and 20 action fields and to ultimately operationalise the action fields into 23 indicators (Table A1) [20]. The indicators are based on secondary data to ensure proper data availability and are focusing on the urban system. Most of the data is available on the city level / macro-scale. Higher resolutions, e.g. district, suburb, or street level, are less accessible. Therefore, a downscaling in order to monitor and evaluate changes on the specific scale pertaining to the adaptation action is not yet possible. Further, the lower scales' alterations are less represented by the system-indicator set because of the resolution issue.

Example: If through an adaptation action, ground sealing in one street is removed, the indicator “Degree of unsealed ground” will improve, but not significantly, due to the scaling.

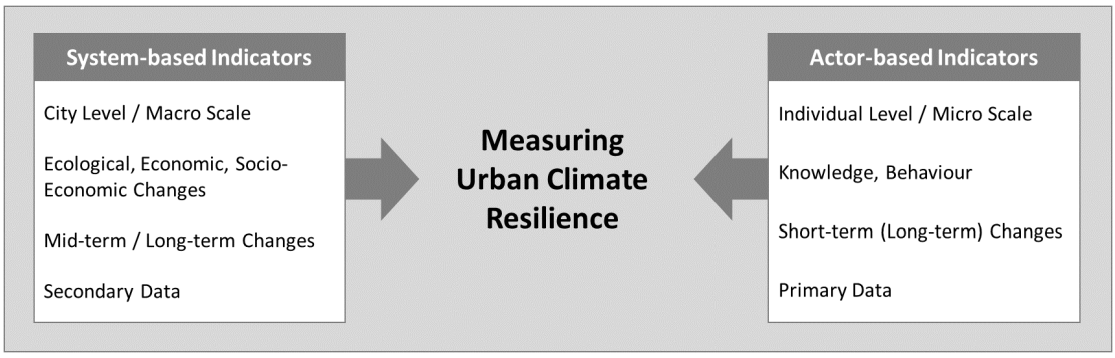


Fig. 1. Monitoring and evaluation framework for climate change adaptation measurements in the context of urban resilience.

Accordingly, the system-indicator set can show mid- or long-term changes regarding the overall urban system. In order to accelerate the learning process regarding climate change adaptation and resilience, measuring short-term changes became essential. Beside the fact that only a few secondary data indicators are available on the micro-scale, actors of adaptation are less involved in the monitoring and evaluating adaptation measurements, even if they have a pivotal role [78]. Furthermore, the 14 cooperating projects are using co-production approaches. Against this backdrop, outcomes and goals are not clearly defined at the beginning of the adaptation measurement [43], which is challenging for any subsequent evaluation. Taking these aspects into account, we decided to address the micro-scale changes produced by adaptation-action through actor-based indicators (Fig. 1).

2.2. Why is individual agency essential regarding urban climate adaptation and resilience?

Holling [29] introduced the resilience concept in the ecological context for the first time in 1973. Meanwhile, it has been applied to many different scientific fields [44;45] – e.g. ecological resilience [1], engineering resilience, social resilience [1,5,22;37] or social-ecological resilience. In our research, we are focusing on the social-ecological resilience approach [1,17] where socio-economic and ecological systems [77] are understood as one social-ecological system [8]. Within the scope of social-ecological systems, both systems' interdependencies and concatenations are mainly addressed to reduce and prevent the separation between human and natural systems [23], a human construct [8;77]. Hence, resilience is understood as a dynamic and relational process without a final resilient state of the social-ecological system [37].

Within MONARES, we applied the resilience concept to the urban scale and the context of climate change. Based on an integrative development process (see [20,46] we define urban climate resilience as follows: “The climate resilience of a city depends on the ability of its subsystems to anticipate the consequences of extreme weather and climate change, to resist the negative consequences of these events and to recover essential functions after disturbance quickly, as well as to learn from these events and to adapt to the consequences of climate change in the short and medium-term, and transform in the long term. The more pronounced these abilities are, the more resilient a city is to the consequences of climate change. All abilities are important.” [20].

Actors perform the abilities of an urban system [78]. As a result, the individual sense of responsibility and individual activity is essential for the transformation process. Individuals play a pivotal role in performing social change and transformation [76] due to their specific behaviour, identities, norms and values [52,55]. The individual agency to influence climate change adaptation is essential for building resilience since it enables everyday adaptation [4,9,11,16,22,26,51,53,55,75,76]. Consequently, it is crucial to understand the individual agency regarding climate resilience [11,24,74].

In detail, we apprehend individual climate resilience agency as the personal, independent ability for reflective decision-making and action-taking in the context of enhancing climate resilience. This study focuses on the fundamental actor-based aspects (e.g. empowerment, knowledge, learning-effects, motivation), which can improve ICRA - institutional structures [27] are not addressed yet.

One of the basic aspects of action-taking and empowerment is knowledge [43,78]. Avelino and Rotmans [2] pointed out that knowledge is directly related to “the conditions of power: access to resources, strategies to mobilise them, skills to apply these methods and the willingness to do so in the pursuit of a specific goal”. As Muñoz-Erickson et al. [48] discuss, knowledge is essential to construct shared beliefs, discourses, practices, policies, and visions, e.g. in a city or a social group. Consequently, knowledge is the basis of changing practices and behaviour [80, 64]. In-depth and diverse knowledge is essential for empowering actors to adaptation and robust decision-making [80]. In the context of adaptive capacity, knowledge is highly recognised as both determinant and indicator [78] and tightly intertwined with other dimensions in the context of adaptation [31,78]. Against this backdrop, we decided to use knowledge as the starting point for measuring the changes in ICRA.

Resilience is a comprehensive, context- and place-specific concept for which no consistent definition was achieved yet. In existing indicator sets, learning and knowledge are defined vaguely and are addressed in many different ways [61]. In order to measure individual changes and learning processes, it is challenging to define [10]: What are the generally accepted aspects that everybody should know about resilience? What is right or wrong regarding resilience? As these questions cannot be answered universally, also approaches of measuring knowledge input and knowledge output [34] are not fitting well in the resilience context. Therefore, we decided to measure knowledge as well as action changes by self-assessment questions.

3. Materials and methods

Given the theoretical considerations pointed out above, we wanted to know if the vital role of enhancing actor knowledge, competence and performance can be verified by applied research. Therefore, in a preliminary study, an exploratory survey was conducted with the 14 cooperating projects. In order to identify overarching impact objectives, we inquired about the project-specific impact targets. Essentially, improving individual knowledge, competence, and performance is crucial for all projects.

3.1. Framework for individual climate resilience agency

Including these results and further literature review, we developed a framework for measuring individual climate resilience agency. The aim was to design a tool which can be used for both (1) onetime assessment and (2) repetitive measurement. Repeated measurements are essential for monitoring changes over a certain period and evaluating the process as a whole, whether applied during a particular intervention or long-term monitoring and evaluation, e.g. in a city, as formative evaluation.

As resilience is context-specific, complex, and a broad concept, there are no quantifiable knowledge items that can be addressed in a survey to measure changes. Therefore, we chose to measure preconditions that can enhance the ICRA (Fig. 2). These preconditions are based on the results of the exploratory survey mentioned above, impact research within participatory measurements, and action theory; especially on the research of knowledge, competencies and performance [39]. Subsequently, the terms “knowledge” and “action” are deconstructed into the aspects knowledge, competence and performance.

The basis - or capacity - of and for action is knowledge [39,64]. Competence is understood as the ability to deal with knowledge (implicit and explicit) itself, apply knowledge, and interpret it [19]. Further, competence includes three components: qualification, willingness and responsibility to address a challenge [56]. Performance describes the transfer of knowledge and competence to effective (social) action [19].

In order to dissect these aspects to a measurable framework, we deduced the dimensions knowledge [k], (subjective) learning effects [le], competence of judgement [c] and interest [i] [28]. Further, we included (previous) experience [ex] and divided action into current action [ca] and future action [fa]. These components are building the dimensions of ICRA.

Based on the developed framework, we derive individual indicators for each dimension (Table 1). In the following section, each selected dimension is outlined with its indicators.

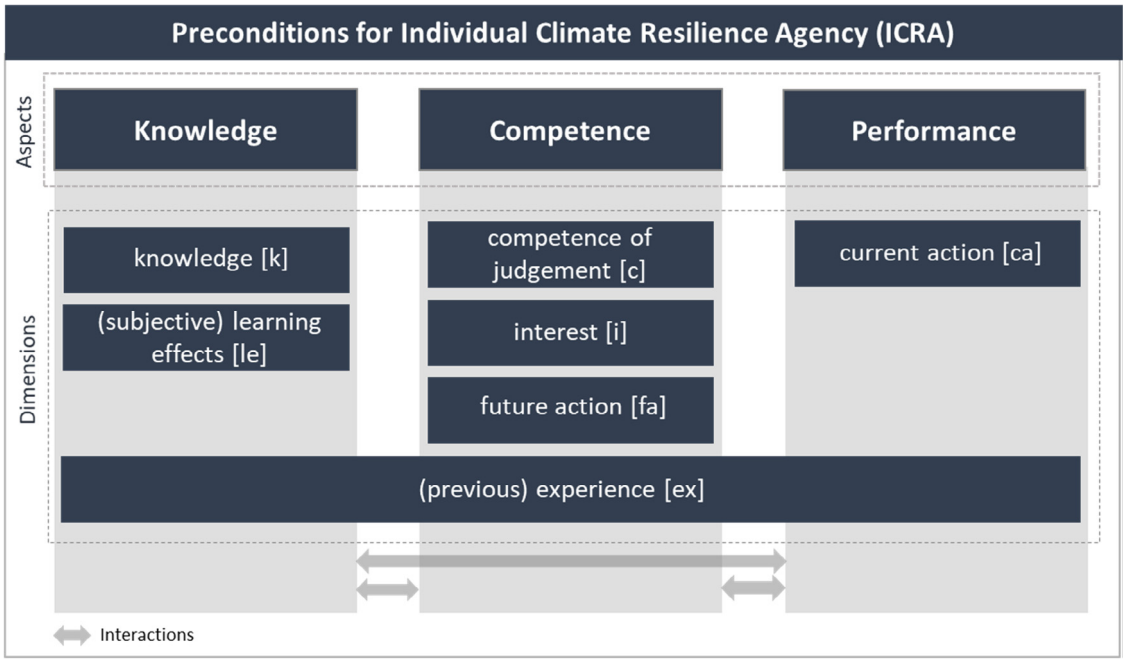


Fig. 2. Deconstructed preconditions for individual climate resilience agency (ICRA).

The *aspect knowledge* is constituted through the dimensions knowledge and learning effects. Within the knowledge [k] dimension, we focus on the narrow understanding of knowledge and current expertise status. Basic knowledge (Indicator K1.1.), expertise (Indicator K1.2., K1.3) and comprehensive expertise (Indicator K 1.5, K1.6.) are the indicators to measure knowledge. Learning or (subjective) learning effects [le] are the main objectives of the aspect knowledge as explicit and implicit knowledge is obtained. The dimension (*subjective) learning effects* focuses on learning effects induced by an intervention. Different grades of learning effects are included. It differs from simple learning effects (knowledge raising – Indicator L1.1, L1.2) to complex learning effects (transfer to daily life – Indicator P1.1, P1.2, P1.3, P1.4) [28].

The *aspect competence* consists of the dimensions competence of judgement [c], interest [i], and future action [fa]. The competence of judgement sums up the cognitive competence of retrieving knowledge (Indicator K1.4), the current ability to use this knowledge, e.g. for decision and reflective communications processes (Indicator K1.2) are assessed [28]. The future action dimension details whether the implemented measurement impacts the self-perception of individual future behavioural changes (P 2.1, P2.2). These aspects are an essential component of an actor's willingness to perform changes in future. The interest dimension includes individual motivation and measurement-caused individual motivation changes for future engagement (P2.1, P2.2.) [28].

The main objective of the aspect *performance* is the dimension current action, which reflects the participant's current performance. The indicators assess whether actors address the topic already in their daily actions in both professional and private routines. Within this dimension, the current behaviour regarding working or engaging in the subject's context (K2.4, K2.5, K2.6, K2.7) is assessed. Further, (daily) behaviour (P1.1, P1.2, P1.3, P1.4) and the changes thereof caused by measurement are questioned.

In the dimension (previous) experience, the personal history with climate-induced events is assessed. Experience is important to assess the current status of knowledge, competence of judgement and subjective learning effects. Further, experience is influencing all other dimensions. Within this dimension, contact with the subject (K 2.1), intensity and durability of experience with the subject (K2.2, K2.3) and experience in acting in the context of the subject (K2.4, K2.5) are assessed.

In the next step, these individual indicators are ordered to composite indicator panels, so that user perception and applicability is enhanced. The individual indicators were operationalised to indicator questions and were transferred into a standardised survey tool. Because of the difficulties pointed out in chapter 2.2, we chose to use self-estimation questions with a seven-point Likert scale (strongly agree – strongly disagree) (Table A2, Table A3).

Table 1
Overview of the developed indicators and their assignment to the ICRA dimensions.

Item	Individual indicators	Dimension
K1.1	General knowledge of [topic]	k
K1.2	Explanatory skills in the subject area	k, c
K1.3	In-depth knowledge in a subfield of [topic]	k
K1.4	Information assessment	c
K1.5	In-depth knowledge of several areas of [topic]	k
K1.6	Expert knowledge on [topic]	k
K2.1	Contact with [topic]	ex
K2.2	Experience with [topic] (intensity)	ex
K2.3	Experience with [topic] (durability)	ex
K2.4	Experience on implementing projects concerning [topic]	ex, ca
K2.5	Experience in leading projects concerning [topic]	ex, ca
K2.6	Consulting abilities regarding [topic]	ca
K2.7	Expert status with regard to [topic]	ca
L1.1	Increase of knowledge on [topic]	le
L1.2	Awareness-raising regarding [topic]	le
P1.1	Action changes in the professional context	le, ca
P1.2	Application of [topic] in everyday working life	le, ca
P1.3	Action changes in the private context	le, ca
P1.4	Sensitisation of others regarding [topic]	le, ca,
P2.1	Motivation / Interest for further participatory involvement	fa, i
P2.2	Motivation / Interest to further initiating engagement	fa, i

3.2. Study sample of test implementation

We conducted an exploratory standardised online survey to test the developed survey tool, using the Software LimeSurvey Version 3.23.3,

within the 14 cooperating research projects. A trend study design with two waves was applied (2019, 2020) [62]. The 14 research projects are operating in 33 municipalities throughout Germany. We asked the project leaders to send the survey to all project team members (~150). Accordingly, the respondents are professionals who are implementing climate change adaptation measurements. A total of n = 59 in 2019 and a total of n = 53 in 2020 surveys were completed (see Table 2). Both times females were slightly overrepresented, as well as respondents who are working at research institutions (46% in 2019, 64% in 2020). Due to the institutional challenges of research projects, we expected high staff fluctuations working on specific projects. In order to trace how many participants answered both times (10), we included a personal indicator code into the survey. To further reduce panel conditioning, previously given answers of the first wave were not accessible to respondents who answered twice.

3.3. Statistical and empirical validation of individual climate resilience framework

This study validated the composite indicators with empirical data using SPSS 26. Hence, we use Cronbach Coefficient Alpha (c-alpha) as a coefficient of reliability. In reliability/item analysis, c-alpha is the most prevalent measure of the internal consistency of survey items [54]. It evaluates how well a set of individual indicators gauges the same underlying construct [54]. A high "reliability" is indicated by a high c-alpha and reflects a good measurement of a latent concept through the various individual indicators [54]. In compliance with OECD [54], we used 0.6 as the cut-off value.

Furthermore, we implemented an exploratory factor analysis (EFA) and principal component analysis (PCA) with the empirical data to compare the overall consistency of theory-driven composed indicators and the empirical conducted composition. PCA is a technique for data reduction to reveal latent data structures. Further, the methodology can be applied to develop and revise measuring instruments [18,32]. PCA extracts variables into new components [32] which can be used to develop composite indicators. The extraction is based on the correlation between the variables. Components can be interpreted as the correlation of each variable with the component. Therefore, each variable has a loading regarding each component, which is expressed in the component matrix. The square of the factor loading is representing the amount of variance, which is explained by each variable [30]. Finally, we applied the developed tool to an example use-case of repetitive measurement with empirical data.

4. Results

This section starts by presenting the results of the operationalisation process of the individual climate agency, showing the set of indicators and measuring questions. Section 4.2 shows the results of the statistical and empirical validation of the framework and indicators. Section 4.3 concludes by the monitoring and evaluation results of the survey in 2019 and 2020.

4.1. Dimensions, indicators and operationalisation

The developed indicator set consists of five composite indicator panels (Table 3). The dimensions *knowledge [k]* and *competence of judgement [c]* are refined by six questions and concise in the composite indicator panel *Basic Knowledge (K1)*. Further, *Experience and Current Action (K2)* integrates seven questions regarding the dimensions *(previous) experience [ex]* and *current actions [ca]*. The composite indicator panel *Learning Effects (L1)* pronounces the gained learning effects (e.g. through the project) and includes parts of dimension *learning effects [le]*.

The last two indicator panels are focusing on performance or action. *Ongoing (Behaviour) Changes (P1)* includes the dimension *subjective learning effects [le]* and *current action [ca]*. *(P2) Future Engagement* addresses the dimensions *future action [fa]* and *interest [i]*.

The questions are organised in two question groups (Table A2, Table A3). Questions on the indicator panels *K1* and *K2* are cumulated into one group because they deal with the current self-estimation regarding knowledge and competencies. The second group formed with *L1, P1* and *P2* is embedded in the learning and impact context of the adaptation measurements.

4.2. Validation of framework and indicators

4.2.1. Statistical validation

The test of reliability with c-alpha was indicative of a very good consistency regarding the theory-driven composite indicators (Table 4). In 2019, all composite indicators were internal consistent applying the cut-off criteria 0.6. Also in 2020, the indicators showed a high overall internal consistency with *K1, K2, P1* and *P2* above the cut off criteria. Only *L1* was slightly below the cut-off criteria with a c-alpha of 0.52.

4.2.2. Empirical validation with principal component analysis

In order to validate the framework with empirically calculated indicators, we first conducted an EFA. The results of the EFA suggests a two-component solution for both question groups. Therefore, we executed a PCA, using varimax rotation, with two components for both question groups relying on the data of 2019.

Group 1 (Table 5) consists of 13 indicator questions. The Kaiser-Mayer-Olkin Measure of Sampling Adequacy was calculated with 0.89; the cumulative total variance explained is 71.95% with two components. Two indicator questions (K1.5 and K1.6) are loading on both components. Thus, these items are correlating with both components and are also influencing both. Regarding these results, the PCA suggests two composite indicators – Indicator 1 (C1) with the items *K1.1, K1.2, K1.3, K1.4, K1.5*, and *K1.6*; Indicator 2 (C2) including *K1.5, K1.6, K2.2, K2.2, K2.3, K2.4, K2.5, K2.6* and *K2.7*.

Group 2 (Table 6) consists of 8 indicator questions. The Kaiser-Mayer-Olkin Measure of Sampling Adequacy was calculated as 0.77; the cumulative total variance explained is 70.54% with two components. All items are assigned to one component. Regarding these results, the PCA suggests two composite indicators – Indicator 1 (C3) with the items *L1.1, L1.2, P1.1* and *P1.3*; Indicator 2 (C4) including P1.2, P1.4, P2.1 and P2.2.

In most cases, the theory-driven framework's indicator structure is verified by the PCA (Table 5 and Table 6). In general, the framework consists of five composite indicators, whereas by applying the PCA, four components - and therefore four composite indicators - are revealed. The composite indicator *K1* is identical with the data-driven composite indicator C2. However, the items *K1.5* and *K1.6* are loading on both components (Table 5). Accordingly, the data-driven analysis recommends complementing *K2* with the items *K1.5*

Table 2
Overview study sample 2019 and 2020.

		Gender				Profession			
Year	*n*	*Female*	*Male*	*Divers*	*NA*	*Research*	*Municipality*	*Planning office*	*Other*
2019	59	35	24	0	3	36	15	2	4
2020	53	29	23	1	0	34	16	1	2

Table 3
Overview of indicators, dimensions and indicator questions of the developed framework.

Composite indicator	Item	Individual indicators	Indicator questions	Dimension
K 1: Basic Knowledge	K1.1	General knowledge of [topic]	"I generally know a lot about urban climate resilience."	k
	K1.2	Explanatory skills in subject area	"I can explain the concept of urban climate resilience to others."	k, c
	K1.3	In-depth knowledge in a subfield of [topic]	"I have in-depth knowledge of **one** sub-area of urban climate resilience."	k
	K1.4	Information assessment	"I can classify new information well into the context of urban climate resilience."	c
	K1.5	In-depth knowledge of several areas of [topic]	"I have an in-depth knowledge of **several** areas of urban climate resilience."	k
	K1.6	Expert knowledge on [topic]	"I consider myself an expert in the field of urban climate resilience."	k
K 2: Experience and Current Action	K2.1	Contact with the [topic]	"I already had much contact with the topic of urban climate resilience before the project started."	ex
	K2.2	Experience with the [topic] (intensity)	"I have already dealt with the topic of urban climate resilience very intensively."	ex
	K2.3	Experience with the [topic] (durability)	"I have been working on the topic of urban climate resilience for a long time, already."	ex
	K2.4	Experience on implementing projects concerning [topic]	"I am very experienced in implementing projects in the context of urban climate resilience."	ex, ca
	K2.5	Experience in leading projects concerning [topic]	"I am very experienced in **leading** projects in the context of urban climate resilience."	ex, ca
	K2.6	Consulting abilities regarding [topic]	"I advise others in the context of urban climate resilience."	ca
	K2.7	Expert status with regard to [subject]	"I am often invited to panel discussions regarding urban climate resilience."	ca
L 1: Learning Effects	L1.1	Increase of knowledge on [topic]	"… I have gained new knowledge about urban climate resilience. "	le
	L1.2	Awareness-raising regarding [topic]	"…I notice the terms *climate resilience* and *climate adaptation* more often in the media."	le
P 1: Ongoing (Behaviour) Changes	P1.1	Action changes in the professional context	"…my actions have changed in the professional context."	le, ca
	P1.2	Application of [topic] in everyday working life	"…I try to integrate the concept of urban climate resilience into my everyday professional life outside of the project."	le, ca
	P1.3	Action changes in the private context	"…my actions have been extensively influenced."	le, ca
	P1.4	Sensitisation of others regarding [topic]	"…I also try to sensitise others regarding the topic of urban climate resilience."	le, ca,
P 2: Future Engagement	P2.1	Motivation / Interest for further participatory involvement	"…I would like to get involved in further projects in the field of urban climate resilience."	fa, i
	P2.2	Motivation / Interest to further initiating engagement	"…I would like to initiate further measures in the context of urban climate resilience."	fa, i

Table 4
Results of the test of reliability with Cronbach coefficient alpha.

		2019 (t1)		*2020 (t2)*	
	n of items	*n of cases*	*c-alpha*	*n of cases*	*c-alpha*
K1	6	58	0.87	51	0.87
K2	7	58	0.95	51	0.91
L1	2	57	0.71	52	0.52
P1	4	57	0.82	50	0.72
P2	2	56	0.84	52	0.83

and *K1.6*. Also, the dimensions *L1* and *P2* are confirmed by the data analysis. Only the dimension *P1* would be split partially to *L1* and *P2* within this sample data set (Table 6). Overall, the results validate the developed individual climate resilience agency framework .

4.3. Monitoring and evaluation of individual climate resilience agency

The temporal comparison shows an overall increase in climate resilience across all dimensions. In 2019 (Fig. 3), *Basic Knowledge (K1), Learning Effects (L1)* and *Future Engagement (P2)* were rated with 5.3 and already relatively high resilience score. *Future Engagement (P2)* also shows the highest increase with +0.5. *Basic Knowledge (K1)* increased by +0.2 and *Learning Effects (L1)* only by +0.1. *Ongoing (Behaviour) Changes (P1)* are rated 2019 with 4,3 and increased by +0.3 and reveal a positive trend. *Experience and Current Action (K2)* presented the lowest score overall and remained unimproved.

Considering the individual indicators in more detail, the mean values improved slightly for most items. Within the composite indicator *K1*, the items *K1.3, K1.4* and *K1.5* increased their already high scores by +0.3. The mean of *K2.6* increased by +0.5 to 4.9 in 2020, which is also the highest rating in the composite indicator *K2*. Therefore, the individual indicators of K1 and K2 reveal high improvements regarding the respondents' consulting abilities, with only minor changes regarding pre-existing experience with the topic. Simultaneously, the expertise and comprehensive expertise *(K1.3, K1.4, K1.5)* also improved. Respondents noted an increase of knowledge *(L1.1)* during the measurement by +0.4 to a mean of 6.3.

Within the composite indicator *P1*, two items *(P1.1 and P1.2.)* raised by +0.5 to means of 4.4 and 4.0 in 2020. In addition, *P1.3* improved by +0.3 to a mean of 4.8. These changes state improvements regarding the behaviour changes in professional as well as in private contexts. Moreover, both items of *P2* increased. *P2.1* changed by +0.3 to a mean of 5.8 and *P2.3.* raised by +0.7, which is the highest change rate in the study, to a mean of 5.9. Thus, the ICRA dimensions of future action and interest were improved by the measurement.

Besides the positive changes, *K1.2* (t1: 5.7, t2: 5.6), *K.2.3* (t1: 3.3, t2: 3.2), *K2.4* (t1:3.0, t2: 2.8), *L1.2* (t1: 4.6, t2: 4.6) and *P1.4* (t1: 5.2, t2: 5.1) were slightly lower in 2020 than in 2019 (see Fig. 4).

5. Discussion

In Section 3, we built indicators and a tool to monitor and evaluate climate resilience agency. We then validated the framework, its indicators and questions with empirical data gathered within the MONARES

Table 5
Rotated Component Matrix. Indicator questions of composite indicators K1 and K2 (2019).

Item	component Indicator question	Factor loadings 1	2
K1.1	"I generally know a lot about urban climate resilience."		,732
K1.2	"I can explain the concept of urban climate resilience to others."		,852
K1.3	"I have in-depth knowledge of one sub-area of urban climate resilience."		,674
K1.4	"I can classify new information well into the context of urban climate resilience."		,815
K1.5	"I have an in-depth knowledge of several areas of urban climate resilience."	,563	,546
K1.6	"I consider myself an expert in the field of urban climate resilience."	,629	,560
K2.7	"I am often invited to panel discussions regarding urban climate resilience."	,833	
K2.6	"I advise others in the context of urban climate resilience."	,801	
K2.4	"I am very experienced in implementing projects in the context of urban climate resilience."	,873	
K2.5	"I am very experienced in leading projects in the context of urban climate resilience."	,878	
K2.3	"I have been working on the topic of urban climate resilience for a long time, already."	,820	
K2.2	"I have already dealt with the topic of urban climate resilience very intensively."	,776	
K2.1	"I already had much contact with the topic of urban climate resilience before the project started."	,789	
	Extraction Method: Principal Component Analysis.		
	Rotation Method: Varimax with Kaiser Normalization.		
	a. Rotation converged in 3 iterations.		

Table 6
Rotated component matrix. Indicator questions of composite indicators L1, P1 and P2 (2019).

Item	component Indicator question	Factor loadings 3	4
L1.1	"… I have gained new knowledge about urban climate resilience. "	,704	
L1.2	"…I notice the terms *climate resilience* and *climate adaptation* more often in the media."	,823	
P1.1	"…my actions have changed in the professional context."	,864	
P1.3	"…my actions have been extensively influenced."	,831	
P1.2	"…I try to integrate the concept of urban climate resilience into my everyday professional life outside of the project."		,697
P1.4	"…I also try to sensitise others regarding the topic of urban climate resilience."		,846
P2.1	"…I would like to get involved in further projects in the field of urban climate resilience."		,849
P2.2	"…I would like to initiate further measures in the context of urban climate resilience."		,844
	Extraction Method: Principal Component Analysis.		
	Rotation Method: Varimax with Kaiser Normalization.		
	a. Rotation converged in 3 iterations.		

project. Finally, we implemented the validated methodology by monitoring and evaluating climate resilience agency in 2019 and 2020. In the following, we discuss the results regarding the validation of our methodology. We discuss the monitoring and evaluation results and their implications regarding adaptation measures and the main objective of increasing climate resilience which equals contributing to a sustainable future.

5.1. Statistical and empirical validation of the methodology

The analysis results with c-alpha show the internal consistency of the theory-driven developed composite indicator set. Validated against the PCA, it became apparent that most of the individual indicators are structured in the same way by empirical data, yet in some cases, a different composition is also conceivable. Nonetheless, the structure of the theory-driven indicators has many benefits for practitioners. Firstly, the five composite indicators are giving a more detailed picture of the situation than four indicators. Secondly, a PCA needs to be conducted in order to calculate the specific factor loadings and the specific structure of the indicator composition for the specific sample.

Consequently, the composition of the composite indicators differs slightly every time. However, a comparison between a first and a second survey in a city, not to mention between cities, is not viable. Transparency and replicability are enhanced in the theory-driven indicator set for politics and practitioners. As these aspects are equally crucial for governance and communication, the indicator set can contribute to these essential, resilience-enhancing processes.

5.2. Individual climate resilience agency

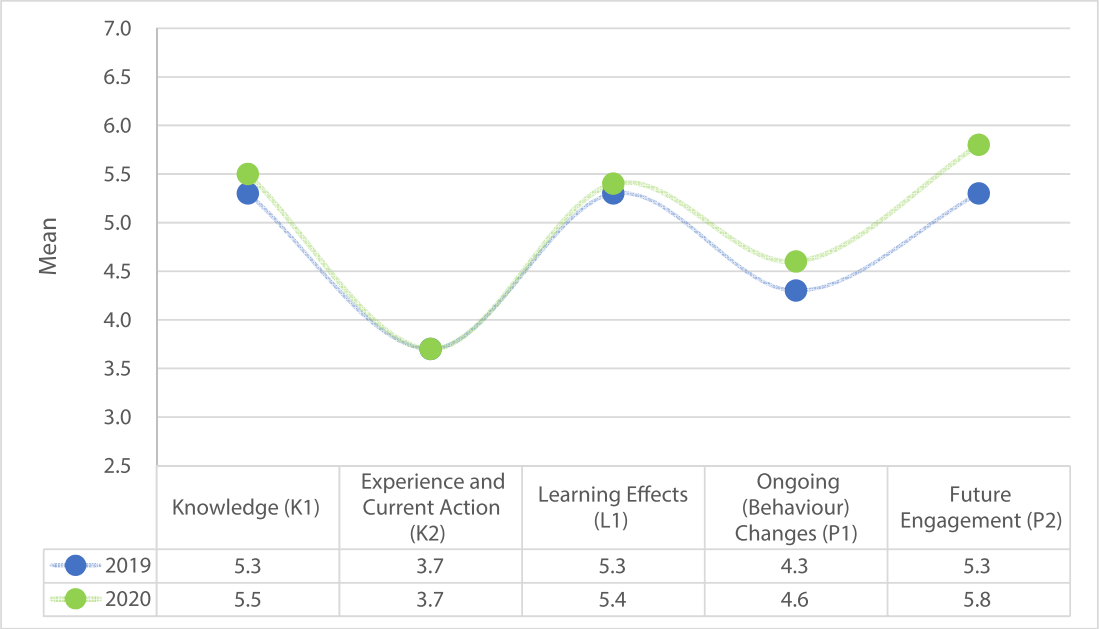
Overall, the individual climate resilience agency was enhanced during the 14 projects. Generally, the dimensions *Basic Knowledge (K1), Learning Effects (L1)* and *Future Engagement (P2)* are high, with baseline means of 5.3, which further increased during the year. A clear gap is reported to the other two dimensions closer related to the previous experience *(Experience and Current Action (K2))* and action changes *(Ongoing (Behaviour) Changes (P1))*, which both record baseline mean values below 4.5. Regarding Experience and *Current Action (K2),* almost no change is observed. We assign these findings to the particular set. As pointed out above, the sample chosen for this exploratory survey consists of researchers, mostly working in applied research projects implementing climate change adaptation interventions. Thus, they are likely to have a relatively high *Basic Knowledge (K1)* regarding resilience. Considering the individual indicators, it became apparent that *K1.2* has a slightly lower score in 2020 than in 2019, whereas the highest increases are recorded by *K1.3* (+0.3), *K1.4* (+0.3) and *K1.5* (+0.3), which indicates learning effects.

Ongoing (Behaviour) Changes (P1) enhanced by +0.3. High changes (+0.5) are recorded for *P1.1* and *P1.2*, which can be explained with the low grade of long-term experience and experience in implementing projects regarding climate resilience of the sample. Besides *P1.1* and *P1.2,* also *P1.3* raised by +0.3, which demonstrates the projects' positive influence regarding private action changes. Additionally, to these positive developments, also the mean of *P2 (Future Engagement)* increased by +0.5. Notably, the improvement (+0.7) of *P2.2 (Interest for further initiating engagement)* witnesses the projects' positive influences. Hence, most of the respondents are highly motivated to initiate further projects that facilitate urban climate resilience enhancement.

Nevertheless, the findings demonstrate that transferring knowledge and awareness into behavioural changes is possible, even within a one-year timeframe. Previous experience seems to have less influence on action changes and knowledge than anticipated initially. Since this might be a particular finding for this specific sample, it needs to be explored in detail within further research.

5.3. Setting the study into a broader context

We aimed to complement the system-based indicators with actor-based indicators in order to design a holistic concept of monitoring and evaluating urban climate resilience (see section 2). Similar to the embrace framework of [38], some frameworks try to address action and learning. For example, the embrace framework defines



	Knowledge (K1)	Experience and Current Action (K2)	Learning Effects (L1)	Ongoing (Behaviour) Changes (P1)	Future Engagement (P2)
2019	5.3	3.7	5.3	4.3	5.3
2020	5.5	3.7	5.4	4.6	5.8

Fig. 3. Means of the composite indicators of 2019 and 2020.

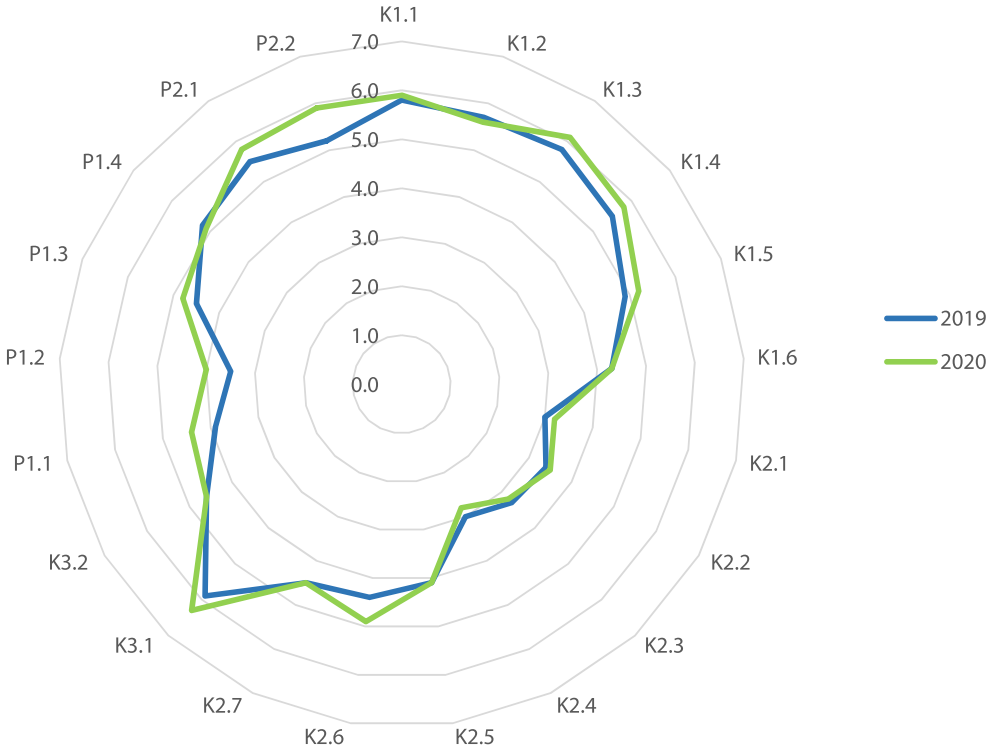


Fig. 4. Individual indicator means of Individual climate resilience agency of 2019 and 2020.

community resilience with three dimensions, comprised of Learning, Action, and Resources and Capacities. Resources and Capacities are similar to system-based indicators (Table A1). In comparison to the presented research, Action and Learning cover aspects of this research as well. The indicators implemented within embrace measure Action and Learning more on a system level than the individual resilience level. Knowledge is not explicitly mentioned either because the individual resilience remains unmeasured. Overall, the presented research aligns and complements existing approaches.

Integrating the actor-based indicators into the set of system-based indicators is essential. In light of this finding, we suggest assigning the ICRA approach within the dimension Society and action field

"Knowledge and risk competence" of the MONARES indicators [46,47]. Nevertheless, both indicator sets can be used independently.

5.4. Challenges: Case study, primary data and accessibility

One influential factor has changed in the study sample between 2019 and 2020. During MONARES, we noticed high fluctuations of the staff working on the specific projects. This was confirmed by the traceability measure to include a personal indicator code into the survey in order to distinguish how many people answered both times. Considering these facts, lower rates in *K2.3* and *K2.4* are making sense within this sample. Further, low rates of *K2* also indicate that urban climate resilience adaptation is a relatively new field in Germany, even in research.

Applying an indicator set alongside the challenge of gathering primary data is always connotated with significantly increased effort and is both time-consuming and resource-dependent compared to relying on secondary data. Especially in the context of municipalities, resources and competence regarding statistically representative surveying are limited. However, since important factors of climate resilience, especially individual climate resilience, are not yet included in existing data sources, primary data are necessary to monitor and evaluate resilience building, either within adaptation projects or the whole city.

5.5. Policy linkages and implications

Several international agreements include building resilience and see the concept as a cornerstone for future well-being. UN-Habitat's New Urban Agenda urges to build resilience of human settlements to disaster and climatic changes [70]. All UN members pledged themselves to the SDGs. The research contributes in achieving several of the goals. Target 1.5 calls "… build the resilience of the poor and those in vulnerable situations, and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters". Goal 11 calls to "make cities and human settlements inclusive, safe, resilient and sustainable". Besides Goal 13 calls for urgent climate action [67]. Nations are obliged by the SDGs to foster and build resilience and all members of the UNFCCC´s Paris Agreement signed to build the resilience of human and natural systems [69]. These agreements on the global scale infuse all scales, in the sense of requiring the creation of policy-conditions and open scopes for actions. Problematically, the local and individual scale is where adaptation measurements are implemented. On this scale, municipalities are responsible for governing, supporting, executing, or creating room for action. However, municipalities have manifold tasks and are frequently low on resources (financial, human, time).

Moreover, adaptation measurements are highly context-specific, limited in time for implementation and often participatory, co-productive and open processes. Regarding these circumstances, supporting the adapting actors and municipalities with an easy-to-use monitoring and evaluation tool is substantial. These tools enhance learning-effects and help to shape climate-resilient pathways. The ICRA approach supports monitoring and evaluation on the individual level and a short-/mid-term timescale, which is an indispensable benefit in an accelerated world. Firstly, it is possible to monitor short-term changes regarding knowledge and action within the measurement. This information can be used as a formative evaluation and support the measurement's adjustment, even in limited implementation time, which can reduce costs and - more importantly - avoid maladaptation. Secondly, the subliminal aim of the adaptation measures to enhance knowledge and foster behavioural changes, which is a precondition for individual agency, can be measured. As adaptation is interlinked with agency, measuring preconditions for its enhancement can also provide more insights into potential long-term effects. In a way, the developed tool enables measurement at a very early stage during the adaptation process, assesses the absolute foundations for individual adaptation potential, and is also applicable in the global north, which is an essential benefit. Further, it is possible to be applied by actors themselves (municipality, research organisation etc.) with no external evaluation being required, which also enhances the learning process.

5.6. Future research

Considering the results and discussion, we identified three potential areas of future research. (1) The exploratory study with employees of applied research projects has provided an insight into individual climate resilience agency and has been utilised for an explorative test of the tool. Nonetheless, a survey conducted within these research projects' participatory actions would have also been a reliable approach for testing the indicators and the survey tool. Because of the projects' different starting points and data security aspects, we did not have the opportunity of further testing. Hence, a next step should be the application of the method to participatory actions. (2) The developed approach might be useful to monitor and evaluate both the adaptation measures themselfes and the induced effects. In addition, on a city-wide scale, the inclusion into the census or other existing surveys might provide insights regarding the necessities of adaption and development. (3) Further research might shed some light on enabling conditions which foster activity and facilitate the transformation of knowledge into action.

6. Conclusions

Climate change-related increase of extreme events combined with global trends such as urbanisation, increasing population and acceleration of social change, require immediate resilience building to provide a sustainable future. Monitoring and evaluation of individual climate resilience agency remain challenging. We attempted to provide an inclusive, comprehensive approach as well as a tool to measure individual climate resilience agency. The approach is validated with empirical data and provides an in-depth understanding of selected parameters in the context of climate resilience.

The overall individual climate resilience agency improved during current adaptation measurements. In the research-oriented setting of our case study *Basic Knowledge (K1), Learning Effects (L1)* and *Future Engagement (P2)* achieved high scores. In contrast, *Experience and Current Action (K2)* and *Ongoing (Behaviour) Changes (P1)* reached lower scores. Except for *K2*, all dimensions increased from 2019 to 2020. The validation of the approach indicated high internal consistency of the items and validation of the dimensions and operationalisation via measuring questions and implementing the survey tool.

Our results show that actor-based measurement regarding individual climate resilience agency is possible and a good opportunity to monitor short-term changes and evaluate specific adaptation measurements. The approach can enhance the management and transformation process for practitioners and contribute to the acceleration of climate-resilient adaptation. As the approach is based on the individual actors – the micro-scale – the tool is not bound to a singular scale and can, be assessed to adaptation measurements and communities in rural regions. Furthermore, context-specific focus adjustments of the indicator-questions, such as replacing the term "urban resilience" with any specific aspect of urban resilience focused within the adaptation

measure, in oder to meet the specific contexts are conceivable and need to be tested.

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CRediT authorship contribution statement

Daniela Wilden: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - original draft, Visualization. **Daniel Feldmeyer:** Conceptualization, Methodology, Validation, Writing - original draft.

Declaration of Competing Interest

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

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Appendix A

See Tables A1–A3.

Table A1
Dimensions, actions fields and indicators of the MONARES indicator set [20].

Dimension	Action field	MONARES indicator set
Environment	Soil and green spaces	Degree of unsealed ground
	Water bodies	State of water bodies
	Biodiversity	Nature conservation and protection areas
	Air	Ventilation status
Infrastructure	Settlement structure	Building density
	Energy	Diversity of renewable energy
		Per capita energy consumption
	Water supply and wastewater management	Number of springs
		Adapted sewer water
Economy	Innovation	Employees in research intensive companies
	Business	Commercial tax per capita
	Economic structure	Diversity of business
Society	Research	Number of research projects
	Knowledge and risk competence	History with extreme events
	Healthcare	Number of doctors
	Socio-demographic structure	Share of citizens ABV6/U65
	Civil society	Associations per 100,000 capita
	Civil protection	Fire brigade volunteers
Governance	Participation	Number of participation processes
	Municipal budget	Depth per citizen
	Strategy, plans and environment	Risk and vulnerability analysis
		Strategies against heavy rain and heat in plans
	Administration	Inter-offices working group regarding risk, climate change and resilience

Table A2
Questiongroup 1.

Now it is a matter of your personal self-assessment. Please indicate how much the following statements apply to you.									
"I generally know a lot about urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I can explain the concept of urban climate resilience to others."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I have in-depth knowledge of **one** sub-area of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I can classify new information well into the context of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I have an in-depth knowledge of **several** areas of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I consider myself an expert in the field of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I had already had much contact with the topic of urban climate resilience before the project started."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I have already dealt with the topic of urban climate resilience very intensively."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I have been working on the topic of urban climate resilience for a long time, already."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I am very experienced in implementing projects in the context of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"I am very experienced in **leading** projects in the context of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree

Table A3
Questiongroup 2.

Please rate the following statements! Through my previous work in the project…									
"… I have gained new knowledge about urban climate resilience. "	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…I notice the terms climate *resilience* and *climate adaptation* more often in the media."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…my actions have changed in the professional context."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…my actions have been extensively influenced."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…I try to integrate the concept of urban climate resilience into my everyday professional life outside of the project."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…I also try to sensitise others regarding the topic of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…I would like to get involved in further projects in the field of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"…I would like to initiate further measures in the context of urban climate resilience."	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree
"… I have gained new knowledge about urban climate resilience. "	Strongly agree	☐	☐	☐	☐	☐	☐	☐	Strongly disagree

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