Justus Liebig University Giessen

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Shaping climate resilient pathways

Integrative approach for monitoring and evaluation of climate resilience and climate change adaptation

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Entwicklung klimaresilienter Pfade: Integrativer Ansatz für Monitoring und Evaluation von Klimaresilienz und Klimaanpassung

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Abstract

Climate resilience and climate adaptation have started to play an essential role in research, international and national politics, as well as at local level. Also in Germany, the impacts of climate change is undeniable. Cities are increasingly facing the challenge of adapting to the (anticipated) impacts and enhancing the climate resilience of the urban system and societies. Urban areas are considered to be highly complex and interconnected adaptive social-ecological systems embedded in the acceleration of climate and societal change. Due to this multi-layered complexity, it is challenging to assess the success of resilience-building measures, while, evaluation is very important to accelerate learning processes, reduce maladaptation and design climate resilient pathways.

The paper aims to develop an integrating, cross-scale (spatial and temporal) monitoring and evaluation approach for climate resilience and adaptation to provide a scientific basis for practical application. For this purpose, a mix-method approach is pursued at the three different levels – intervention, system and actor level. The spatial focus of the study is on Germany.

The results reveal that each scale has specific benefits and limitations with regard to monitoring and assessing climate resilience and adaptation measures. Particularly important is raising awareness and the behavioural change of the actors in the adaptation projects and this underlines the central role of actors in the transformation process. Based on empirically validated indicators for the respective levels, monitoring is possible at the short, medium and long-term levels as well as at the level of individual actors up to the regional system. Drawing on these results, an integrative approach for monitoring and assessing climate resilience and adaptation is derived.

The critical discussion of the research results highlights both the need for further research and opportunities for further development of the integrative approach and the learning and transformation process.

Kurzfassung

Klimaresilienz und Klimaanpassung spielen mittlerweile in der Forschung, in der internationalen und nationalen Politik sowie auf lokaler Ebene eine wesentliche Rolle. Auch in Deutschland sind die Auswirkungen des Klimawandels unübersehbar. Städte stehen zunehmend vor der Herausforderung sich an die (antizipierten) Auswirklungen anzupassen und die Klimaresilienz des städtischen Systems und der Gesellschaft zu erhöhen. Urbane Räume werden als hochkomplexe und miteinander verflochtene, adaptive sozial-ökologische Systeme betrachtet, die in die Beschleunigung des klimatischen und gesellschaftlichen Wandels eingebettet sind. Aufgrund dieser vielschichtigen Komplexität ist es eine Herausforderung, den Erfolg von resilienzsteigernden Maßnahmen zu bewerten. Gleichzeitig ist die Bewertung von großer Bedeutung, um Lernprozesse zu beschleunigen, Fehlanpassungen zu reduzieren und klimaresiliente Pfade zu gestalten.

Die Arbeit zielt darauf ab, einen integrierenden, skalenübergreifenden (räumlichen und zeitlichen) Monitoring- und Evaluierungsansatz für Klimaresilienz und -anpassung zu entwickeln, um eine wissenschaftliche Grundlage für die praktische Anwendung zu schaffen. Hierzu wird ein Mix-Method Ansatz verfolgt der auf den drei verschiedenen Ebenen - Interventionsebene, Systemebene und Akteursebene- durchgeführt wird. Der räumliche Fokus der Studie liegt auf Deutschland.

Im Ergebnis wird deutlich, dass jede Skala spezifische Vorteile und Grenzen in Bezug auf das Monitoring und die Evaluation von Klimaresilienz und Anpassungsmaßnahmen hat. Von besonderer Bedeutung ist die Bewusstseinsbildung und Verhaltensänderung der Akteure in den Anpassungsprojekten. Das unterstreicht die zentrale Rolle der Akteure im Transformationsprozess. Basierend auf für die jeweiligen Ebenen empirisch validierten Indikatoren wird ein Monitoring sowohl auf kurz-, mittel- und langfristiger Ebenen als auch auf der Ebene der einzelnen Akteure bis hin zum regionalen System möglich. Aus diesen Ergebnissen wird ein integrativer Ansatz für das Monitoring und die Evaluation von Klimaresilienz und Klimaanpassung abgeleitet.

Die kritische Diskussion der Forschungsergebnisse verdeutlicht sowohl denweiteren Forschungsbedarf als auch Möglichkeiten zur Weiterentwicklung des integrativen Ansatzes sowie des Lern- und Transformationsprozesses.

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Content

List of Abbreviations

AL	Actors' Level
APA	Aktionsplan Anpassung [German adaptation action plan]
BauGB	Baugesetzbuch [Federal Building Code]
BMBF	Bundesministerium für Bildung unf Forschung [Federal Ministry of Education and Research]
CI	Composite Indicator
COP	Conference of Parties
DAS	Deutsche Anpassungsstrategie [German adaptation strategy]
EU	European Union
GHG	Greenhouse Gas
ICRA	Individual Climate Resilience Agency
IL	Intervention Level
IPCC	Intergovernmental Panel on Climate Change
MONARES	Monitoring von Anpassungsmaßnahmen und Klimaresilienz in Städten [Monitoring of adaptation measures and climate resilience in cities]
MIS	MONARES Indicator Set
MQ	Main research question
PCA	Principal Component Analysis
RCRI	Regional Climate Resilience Index
ROG	Raumordnungsgesetz [Federal Regional Planning Act]
RQ	Research Question
SDG	Sustainable Development Goals
SL	System Level
UBA	Umweltbundesamt [Germany Environmental Agency]
UN	United Nations

UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

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1 Shaping climate resilient pathways?

"Climate change is no longer a long-term problem.
We are confronted now with a global climate crisis.
The point of no-return is no longer over the horizon.
It is in sight and hurtling towards us."
Antonio Guterres, UN Secretary General 2019

July 2021. Western Germany. Within 24 hours, heavy precipitation, in parts between 100 l/m² and 150 l/m², made cities as well as rural regions to settings for an extreme weather event. The stationary, heavy rainfall and water-saturated soils from previous persistent rainfalls since April and especially since the beginning of July led to severe inundation in Western Germany. In this historic flooding, 180 people lost their lives; many people lost their homes and livelihoods. The flood caused billions of euros in property damage and destroyed many crucial infrastructures – e.g. bridges, streets, gas and energy lines, water supply systems, cell towers, railways or schools. Warnings regarding the upcoming weather event had been made by the German Weather Institute (DWD). However, the extent and exact timing of extreme weather events cannot be estimated weeks in advance, but barely a week, sometimes only days before. Due to this event, questions about how to deal with the impacts of climate change, how to reduce economic losses and fatalities, how to prepare and live with uncertainty also entered the public discourse in Germany.

Climate change's challenges to societies are being discussed increasingly in science and politics. However, the spatio-temporal decoupling of the cause-effect chain makes future threats difficult to grasp and ultimately to foresee. Scientists are dealing with projections, simulations, and scenarios to shed light on the nebulous future and understand which challenges societies will face. It is unequivocal that climate change leads to alterations in the frequency, intensity, spatial dimension, magnitude, duration, and timing of extreme weather events and climate events (IPCC 2012). Nonetheless, the exact time, coordinates and magnitude cannot be foreseen. Therefore, anticipating of and adapting to climate change are becoming key issues for societies and pose major challenges for spatial planning, governance, decision-making processes, etc. (Meerow et al. 2016).

Urban regions are particularly affected by these developments, as the potential for loss is very high due to the accumulation of people, services, industries, assets etc. However, cities are not only vulnerable to climate risks – they also play a key role in mitigation and adaptation (UN DESA 2018). Cities already account for 70% of global carbon dioxide emissions and they are responsible for 75% of global energy use (IEA 2021:15). Consequently, urban areas are the main drivers of climate change (IPCC 2014:47), and this role is expected to increase further as many parts of the world continue to urbanise (UN DESA 2018). The high urbanisation rate and proportion of people living in cities make them increasingly responsible for whether the challenges of climate change adaptation and resilience-building can be met. So, while they are part of the problem, they are also part of the solution, as they are centres of innovation and change. Cities have a significant role in the adaptation process and resilience building, as they need to reduce their vulnerabilities (IPCC 2014:47, Mehryar et al. 2022:1).

Against the backdrop of climate change and urbanisation process, the resilience concept is subject to growing attention from academics and practitioners (Rana 2020). For example, the United Nations (UN DESA 2017) have included strengthening resilience to climate-related extreme events in its Sustainable Development Goals (SDGs). The enhancement of resilience is carried out by adaptation actions on the local scale, e.g. within a city. A local action might involve creating and improving green infrastructure to reduce heat in the city and improve water infiltration or awareness rising activities. But, how can local governments, local groups, and actors know if the measures they carry out and their decisions are steering the pathway to resilience? This question brings the measurement of adaptation actions and climate resilience into focus.

Measuring the success of the actions taken is central for different decision-making processes, the further enhancement of climate adaptation measures, the management of the whole social-ecological transformation to a resilient society and the management of resilience building. This places monitoring and evaluation at the centre of climate adaptation and resilience in cities to accelerate learning effects (Bellinson, Chu 2018) and avoid maladaptation. It is challenging to map the success of resilience measures, as cities are considered as complex, multi-layered social-ecological systems (Feldmeyer et al. 2019). Due to accelerating climatic and societal change (Lübbe 2003; Rosa 2003) and increasing uncertainty, dynamics, risks, and multiple simultaneities, monitoring and evaluation of adaptation activities have therefore become even more critical (Nassehi 2008; Rosa 2003).

With that in mind, this thesis aims to support shaping climate resilient pathways by developing an integrated monitoring and evaluation approach. The research relates predominantly to Germany, as most parts of the research were embedded into the research project MONARES – *Monitoring von Anpassungsmaßnahmen und Klimaresilienz in Städten* [Monitoring of Adaptation Measures and Climate Resilience in Cities] funded by the German Federal Ministry of Education and Research (BMBF) and conducted from 2017 to 2020.

1.1 Research objectives

To support and steer a rapid transformation process to establish resilient cities and societies, information on the impacts of such measures is needed. Consequently, this paper strives to develop an integrating cross-scale (both spatially and temporally) monitoring and evaluation approach for climate resilience and adaptation to build a scientific foundation for the practical application, e.g. within local interventions or local governments. Hence, the ensuing research aims to combine a system-based approach, addressing the urban and regional scale as well as the medium- to long-term changes, and an actor-based approach, focusing on the individual scale and short-term changes.

Therefore, the analysis aims to answer the question of how leading actors (e.g. local governments) can identify if their actions (interventions and decisions) contribute to the goals of climate adaptation and the enhancement of climate resilience (MQ). To answer this overarching research question, this thesis addresses the questions how urban climate resilience and climate adaptation interventions impacts can be monitored and evaluated, and how the complexity of social-ecological systems can be deduced to an applicable and integrative monitoring and evaluation approach.

To reflect the multidimensional aspect of this research subject, the thesis is divided into three main parts with different research focal points – intervention level, system level, actor level (see Figure 1). At the intervention level, the research deals with how interventions at the local level can be characterized and assessed. This issue is vital to understand interventions specifically and overarching impact objectives, and which implementation methods are used within these measures to identify similarities between different climate change adaptation interventions. The second level focuses on how climate resilience and the impacts of climate adaptation interventions can be assessed on the system level (e.g. urban system, regional system). Thirdly, at the actor level, the question of how an assessment on the actor/individual level can contribute to monitoring and evaluating adaptation measures and the navigation of climate-resilient pathways is at the centre.

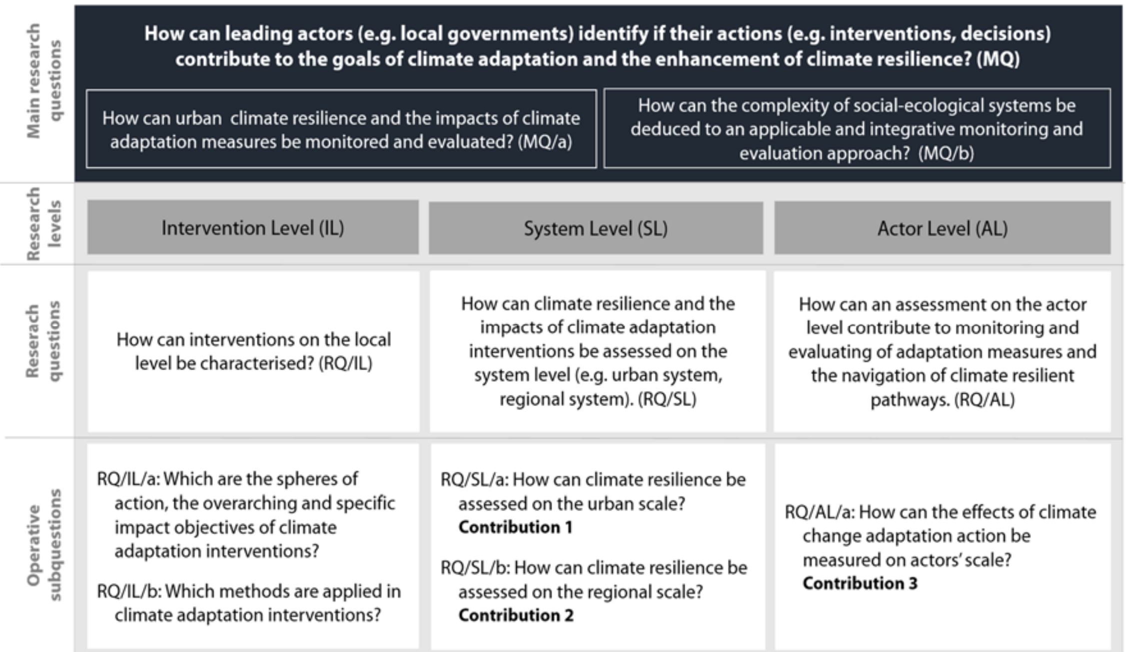

Figure 1: Research structure and questions
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1.2 Pathway through this research

The presented research is designed in a hybrid form of a monographic and cumulative dissertation. Therefore, an overarching argument presents the overall research framework in which the three peer-reviewed publications are embedded. The previous chapter expounded the research objectives and questions and their assignment to the chapters and publications (Chapter 1.1). The conceptual framework, focussing on, e.g. climate change effects, international and national climate policies, as well as the discussion and definition of resilience and adaptation and the role of monitoring and evaluation, is demonstrated in Chapter 2. Chapter 3 provides profound insights into the research approach and methodology. As most parts of the research were embedded in the research project MONARES, this project is outlined in Chapter 3.2. Chapter 4 exemplifies the empirical results. Firstly, basic descriptive statistics and results of the case study are introduced (Chapter 4.1.). Secondly, each article is summarised briefly (Chapters 4.2 and 4.3). Thirdly, the possibilities of integrating the developed concepts and findings into one monitoring approach are introduced and discussed. Chapter 5 reflects on the research aims as well as the limitations of the research and the possibilities of future research, followed by a brief closing statement.

2 Conceptual framework and state of the art

"It is unequivocal that human influence
has warmed the atmosphere,ocean and land.
Widespread and rapid changes in the atmosphere,
ocean, cryosphere and biosphere have occurred."
(IPCC2021b:5)

The following chapters look at the central and theoretical concepts within this thesis. Firstly, the cause for climate adaptation – climate change is discussed, continued by an introduction to the international climate policy, which provides the overall framework for climate resilience and climate change adaptation. Afterwards, the concept of climate-resilient pathways and the complexity of decision-making in the Anthropocene are presented. Building on this, the concept of resilience, especially urban climate resilience, is discussed, followed by the tools for strengthening adaptation. Finally, an interim summary is provided.

2.1 Climate change and its effects

The influence of humanity on the environment, and especially climate change, is unanimously recognised by the scientific community (IPCC 2021a). New climate modulations and further research continuously improve the understanding of these processes (IPCC 2021b:5). However, what is precisely meant by *climate change*? The IPCC (2012:17) defines climate change as "a change in the state of the climate that can be identified […] by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or land use". Thus, climate change leads to alterations in the frequency, intensity, spatial dimension, magnitude, duration and timing of extreme weather events and climate events (IPCC 2012:18-20).

Anthropogenic climate change is the driver and catalyst of many kinds of weather and extreme climate events – such as heatwaves, droughts, heavy precipitation, flooding – worldwide (IPCC 2021b:10). Besides the extreme weather event of 14^{th} July 2021, mentioned at the beginning of this paper, many further extreme weather events took place in 2021 and demonstrated the ongoing climate change. For example, in central USA and northern Mexico, an abnormal cold wave struck in mid-February 2021. A heatwave in Canada and the Northwest US happened with temperatures up to 50 °C. The Mediterranean region of Europe was affected by extreme heat in August, and persistent above-average rainfall in northern South America led to lasting flooding in the northern Amazon basin and pushed the Rio Negro at Manaus to its highest level since records began. Concurrently, many parts of subtropical South America were affected by drought (WMO 2021). All these events were accompanied by economic loss and, at worst, fatalities too.

However, such events will occur more frequently due to climate change. However, these events and circumstances do not come out of anywhere. Climate data underpins these developments. For example, since 1950, extreme hot events have been more frequent and intense (IPCC 2021b:10), with cold waves and other cold extremes occurring less since 1950 (IPCC 2021b:10). The warmest decade (2010-2019) since climate records are now behind us (see Figure 2). However, each of the recent four decades (1980-2020) has been gradually warmer than any decade since 1850 (IPCC 2021b:5). Between 2010 and 2019, the global average surface temperature was between 0.94 and 1.03 °C warmer than pre-industrial levels. Surface temperatures in Europe have risen even more than the global average over the same period, by 1.7 - 1.9 °C. The target set in the Paris Agreement to limit global warming to 2 °C respectively 1.5 °C will be exceeded by 2050 without the introduction of severe restrictions (EEA 2020a). Besides the effect on rising temperatures, the impact on the global glacier retreat, the warming of the upper ocean (0-700 m), the global sea-level rise, the shifting of the climate zones, precipitation changes, to name just a few, are considered as given by the IPCC (IPCC 2021b:6).

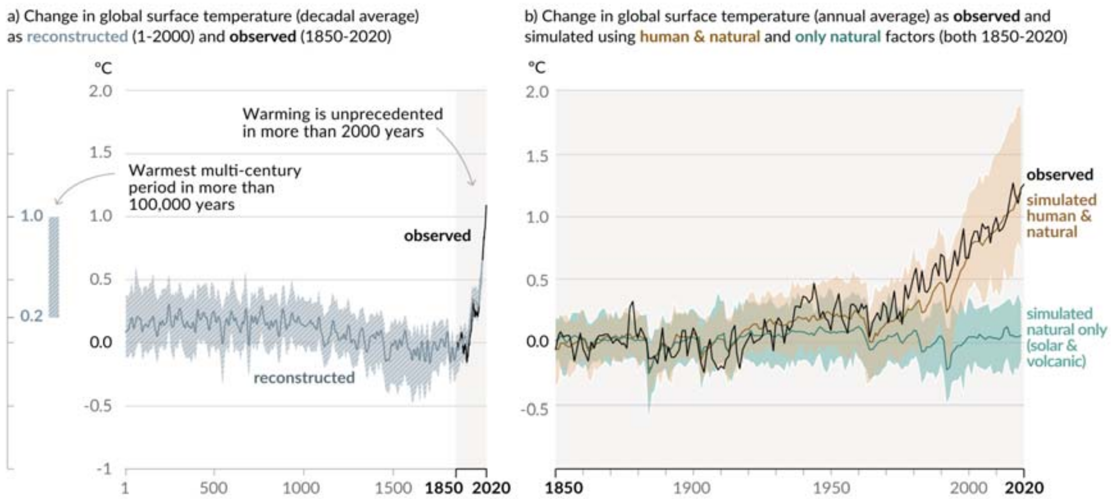


Figure 2: Changes in global surface temperature relative to 1850-1900
Source: IPCC 2021b:7

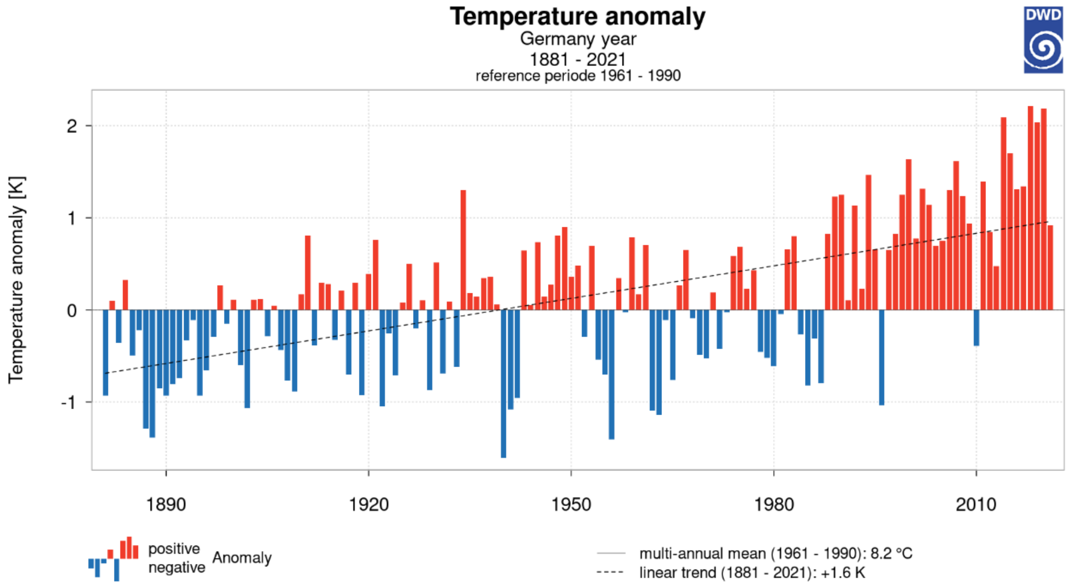


Figure 3: Temperature anomaly Germany per year between 1881 and 2021. Reference period 1961 - 1990 Source: DWD 2021b

Germany is experiencing the impacts of climate change more frequently, also. With a mean temperature of 10.4 °C, 2020 was the second warmest year in Germany since standard records began. The warmest and driest year since weather records began was 2018 (DWD 2021a). Although 2019 and 2020 were not quite as dry, there have never been three years in a row that were this dry and warm since 1881 (DWD 2021a). A decade-by-decade comparison shows that since the 1970s, each decade has been warmer than the previous one. The decade 2011-2021 was 2 °C warmer than the first decade 1881-1890. In global comparison, the temperature in Germany is increasing more rapidly than the global mean. In Germany, the mean value is 1.6 °C (see Figure 3), while the global mean value is +1.1 °C (DWD 2021a).

The impact of climate change is already affecting societies. Especially extreme events, like heatwaves, storms, high precipitation and floods, are already occurring and influencing different aspects of global societies (Folke et al. 2021:840). For example, aspects like livelihoods, health, food security, human security, water supply and economic growth are forecasted to decrease through climate change (Folke et al. 2021:840). Furthermore, the impact of climate change might increase existing socio-economic inequalities worldwide (Folke et al. 2021:840).

In order to limit global warming while living with the already unavoidable impacts of climate change, a far-reaching social-ecological transformation is necessary. Reducing and limiting global warming demands mitigation measures. Adaptation measures are essential to deal with the inevitable impacts of climate change. Mitigation and adaptation must be considered equal, and ideally integrated pillars for a climate-resilient transformation (IPCC 1992:118). Additionally, it is essential to address climate change and sustainable development together within this transformation.

2.2 Climate policies – a brief overview

The question of how to deal with and tackle climate change challenges is highly political as are the decisions, and decision-making processes to solve these challenges (Eriksen et al. 2015; Remling 2018). These decisions influence social relations, affect the essential redistribution of power and resources, and deal with the complexity of reciprocal effects as resilience or adaptation of one system can negatively impact another system or place (Remling 2018, Erkisen et al. 2015). Therefore, besides the scientific discourse on climate change, climate resilience and adaptation became vital issues and key goals within international, European and national policies. As policies are central elements in climate governance, it is vital to understand the process, content and limitations of these policies. Furthermore, it is crucial to reflect the interactions between the governance levels, as climate governance needs to be understood as a multi-level governance system (Folke 2016:6; Fuhr et al. 2018:3,4). The following paragraphs outline the development of climate policies at all levels of the United Nations, the European Union and Germany, focusing on climate resilience and climate change adaptation. However, this thesis does not provide a complete analysis of climate policy, as climate policy, while providing a framework, is not the focus of the research and is beyond the scope of this thesis. Therefore, further essential players like the G7 or G20 are excluded from the analysis. The following chapters summarise the relevant key steps of climate policy against the backdrop of this research and focus on the Global North, with Germany serving as a case study.

2.2.1 Urban climate resilience

The concept of resilience offers the possibility of opening up dialogue and overcoming sectoral ways of thinking in the sense of evolutionary resilience and resilience thinking. Moreover, resilience is a concept that offers the possibility of bringing together the most diverse disciplines and needs in the sense of a "boundary object". Therefore, using the concept of resilience as the basis, it is possible to bring together political actors and institutions with different ideas and actors from different sectors and areas to strengthen resilience. Thus, according to (Béné et al. 2017:13), the concept can be a tool to enable integrative planning.

Keeping this in mind, this paper focuses on the specific resilience of an urban system to the threats of climate change impacts and the challenges of climate change adaptation. The IPCC (2012:5) defined resilience in this context as "the ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner". Thus, this definition omits the learning and transformative character of evolutionary resilience and resilience thinking. Feldmeyer et al. (2019) provide a more detailed definition of urban climate resilience. They discuss: "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." (Feldmeyer et al. 2019:3). When reconsidering this definition, it becomes apparent that in reference to Chapters 3.4.1 to 3.4.5, the social-ecological resilience approach is used for this definition. Moreover, the analysing and managing nature of resilience thinking is also included. Nevertheless, the complexity of the resilience concept becomes clear in this definition, as well as the complexity of the urban system and the challenges posed to the city.

In summary – the authors Feldmeyer et al. (2019:3) suggest that a city should have the capacities to *anticipate, resist, recover, learn, adapt* and *transform*. These capabilities all have different time horizons in relation to a shock event and yet should all be available simultaneously. On the one hand, the occurrence of shock events needs to be *anticipated* in advance. On the other hand, if an extreme event occurs, the city should have the ability to withstand *(resist)* this event as far as possible, e.g. through flexible infrastructures up to disaster control. A resilient city can quickly restore (*recover*) necessary system structures if damage does occur. However, the abilities to *adapt* and *transform* are also central. Even if the city and its systems resist and recover quickly, the medium-term adaptation and long-term transformation of the city system and all its subsystems is fundamental for resilience. This is the only way for anticipated changes be transferred to the future city system.

Based on this definition, Feldmeyer et al. 2019:4 identify five dimensions in their urban climate resilience framework as responsible for the climate resilience of a city – environment, society, governance, economy and infrastructure. These dimensions can be used to assess the climate resilience of a city. Moreover, Feldmeyer et al. 2019 subdivided these dimensions into 24 action fields (see Appendix A1). These action fields form the framework for the indicator development and are therefore also operationalised by Feldmeyer et al. 2019 through an indicator set and presented in Chapter 4.2.1.

2.2.2 United Nations

The main process of the negotiations and development of climate policies began in 1972, at the Stockholm Conference on the Human Environment. This conference was the first United Nations (UN) conference primarily focusing on the environment. The conference was the starting point for establishing the United Nations Environment Programme (UNEP) and initiated the introduction of environmental departments in intergovernmental organisations (Biermann 2021: 62). Fast forward 15 years, the Brundtland Report was published followed by the establishment of the IPCC in 1988 by the UNEP and the World Meteorological Organization (WMO). The IPCC was tasked with assessing and summarising the status quo on climate change research to make this knowledge accessible to policymakers. Two years later, in 1990, the IPCC published the First Assessment Report (Bulkeley, Newell 2015). In this report, the knowledge about the link between human activities, greenhouse gas emissions and global warming pointed at political actors: "We are certain emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases […]. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface." (IPCC 1992:117).

After this first IPCC declaration, the negotiations continued, but the agreements were non-binding, such as the Rio Declaration on Environment and Development (1992) and the Agenda 21 action plan (1992). An important landmark regarding the institutionalisation of climate change negotiations was the implementation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, which was signed by 154 countries. The importance was underlined by the Second Assessment Report of the IPCC, which highlighted that "the balance of evidence suggests a discernible human influence on global climate" (IPCC 1995) in 1995.

Further progress was made, even not as fast as climate scientists proposed. The Kyoto Protocol, the first global agreement to reduce greenhouse gas emissions (Otto 2017), was opened for approval in 1997 and signed by more than 150 countries. However, negotiations were a lengthy process – eight years later, in 2006, the Kyoto Protocol came into force (Otto 2017). In order to develop and ensure a follow-up agreement to the Kyoto Protocol in 2007, the Bali Road Map was approved at COP 13 in Bali. The road map includes the very ambitious Bali Action Plan, which structures a broad process to ensure the Kyoto Protocol's follow-up agreement in 2012 (Otto 2017). However, due to the underestimated complexity of climate change and global solution structures, the process was extended to 2012. In 2012, at COP18 in Doha, the parties approved the outcomes of the five-year process, which reached substantial achievements regarding the enhancement of action on mitigation, adaptation, finance, technology and capacity-building (Otto 2017).

Back in 2009, at COP15 in Copenhagen, the declared goal of an agreed adoption of an international binding succession convention of the Kyoto Protocol failed. The conference's final document, the Copenhagen Accord, declares the first truly global agreement to limit global temperature rise to 2 °C. However, the Copenhagen Accord was a non-binding document (UNFCCC 2010).

Following negotiations and the COP in Doha in 2012, the Fifth Assessment Report of the IPCC was published in 2014 and pronounced the evident influence of humankind on the climate system. In addition, it is set out that the recent changes were already impacting the natural and human systems (Bulkeley, Newell 2015; EC 2021).

2015 marked a significant change within international policies for climate change adaptation. Multiple multilateral agreements and frameworks were implemented within the structures of the UN, the Paris Agreement, the Sustainable Development Goals (SDGs) and the Sendai Framework of disaster risk reduction, which all emphasise the importance of climate change adaptation, resilience and the crucial role of local authorities and actors within the transformation process (EEA 2020b:80).

- *The Paris Agreement*, adopted by 196 parties, is the first legally binding treaty on climate change and, therefore, a milestone in climate change policies. Besides, it is the first binding agreement within the multilateral process, and it is the first international convention that assumes that global climate change adaptation is as essential as global climate mitigation (Magnan, Riberia 2016). On the one hand, the agreements goal is limiting global warming to 2 °C preferentially to 1.5 °C. On the other hand, it aims to enhance countries' capacity building to cope with climate change impacts and develop climate-resilient pathways (UN 2015a).
- *The Sustainable Development Goals* were adopted in 2015 by the United Nations General Assembly (UN 2015b). The SDG framework is designed as an interdisciplinary target concept emphasising the interactions between its different areas and goals. It consists of 17 goals (see Table 1) which in their entirety focus on protecting the planet, ending poverty and guaranteeing peace and wealth by 2030 (UN 2015b). By implementing these targets, it is crucial to take reciprocal effects between the SDGs into account, as both synergies and trade-off effects between the targets can occur (Bansard et al. 2019:114; UNDP 2020). Furthermore, climate change, adaptation and climate resilience are cross-cutting themes; these themes are underlying elements in each SDG. Nevertheless, climate change adaptation and climate

resilience are mainly addressed in the targets detailed in the following list (UN 2015b).

Table 1: Summary of SDG targets addressing climate change adaptation and climate resilience

Target No.	Target name
Target 1.5	Build resilience to environmental, economic, and social disasters
Target 11.5	Reduce the adverse effects of natural disasters
Target 11.6	Reduce the environmental impact of cities
Target 11.B	Implement policies for inclusion, resource efficiency and disaster risk reduction
Target 13.1	Strengthen resilience and adaptive capacity to climate-related disasters
Target 13.2	Integrate climate change measures into policies and planning
Target 13.3	Build knowledge and capacity to meet climate change
Target 13.A	Implement the UN Framework Convention on climate change
Target 13.B	Promote mechanism to raise capacity for planning and management

Source: own table with content from UN 2015b

- *The Sendai Framework for Disaster Risk Reduction* was adopted by the Third UN World Conference on Disaster Risk Reduction. It focuses on both disaster risk reduction and the resilience building of societies (UNDRR 2015). Moreover, the Sendai Framework recognises climate change's importance as a driving force of disaster risk (EEA 2020b:80) and is consequently an essential pillar in climate change adaptation and governance.

Besides these fundamental agreements, the New Urban Agenda was adopted by the United Nations Habitat III (third UN Conference on Housing) and ratified by the UN General Assembly in 2016 (EEA 2020b:80). The New Urban Agenda focuses on implementing SDG 11 – making cities and human settlements inclusive, safe, resilient and sustainable – and strengthening the importance and possibilities of cities within the social-ecological transformation process (UN-Habitat 2017:4, Bansard et al. 2019:113). Additionally, the Agenda highlights the need for a participatory, integrative process across all spatial scales (global, regional, national, subnational and local) and the crucial role of the cities within the implementation process of SDG 11 (UN-Habitat 2017:4).

With these essential pillars and international agreements in mind, the subsequent Conferences on Parties focused on implementing the agreements. In 2019 a further global threat, the Covid 19 Pandemic, arose and set the climate crises, at least for some time, aside. COP26 in Glasgow, which was first scheduled for 2020, was postponed until 2021. Shortly before the conference took place, the IPCC Working Group 1 released its contribution to the Sixth Assessment Report (IPCC 2021b). The report highlights and confirms the impacts of human-induced climate change on extreme events across the globe. At COP26, the *Glasgow Climate Pact* was adopted, which includes the strengthening of climate resilience, agreements on financing adaptation process and on market mechanisms, especially for carbon trading, as well as the completion of the *Paris Agreement rulebook,* which should enhance the transparency of the whole processes (including compliance of the specific climate promises of each country) (UNFCCC 2021). Even if these results are advancing climate policy, they have been criticised as not being far-reaching enough. Among others, the UN Secretary-General António Guterres (2021) pronounced: "The approved texts are a compromise. They reflect the interests, the conditions, the contradictions and the state of political will in the world today. They take important steps, but unfortunately, the collective political will was not enough to overcome some deep contradictions."

2.2.3 European Union

The European Union (EU) is a key player within international negotiation and has pushed the establishment of international commitments forward since negotiations for the Climate Change Convention began in 1991 (Oberthür, Kelly 2008:36). However, despite the EU's international engagement, commitments, and positions, the domestic implementation process of climate policies was prolonged and led to a severe credibility gap (Oberthür, Kelly 2008:40). In order to reduce this gap and become proactive, the EU made an UN-independent commitment in 2007 of achieving at least 20% Greenhouse Gas emissions (GHG) reduction by 2020 compared to 1990 and was a key driver of the beginning of the post-2012 negotiation process at UN level (EC 2007; Oberthür, Kelly 2008). In 2009, the White Paper "Adapting to climate change: Towards a European framework for action", the cornerstone for the EU Climate Adaptation Strategy, was published (EC 2009). In 2013, the finalised EU Adaptation Strategy aiming for enhancing climate resilience in Europe by improving capacities regarding climate change impacts on all levels (local, regional, national and EU) was published (EEA 2020b). In addition to activities designed as cross-sectional, trans-regional and/or cross-border projects, the Strategy also promoted urban adaptation activities by supporting them to take voluntary adaptation action (EEA 2020b:81). Furthermore, the

Adaptation Strategy is crucial for mainstreaming climate adaptation and climate action within EU policy (EEA 2020b:81).

In 2019, the European Green Deal was introduced by the European Commission. The Green Deal includes different spheres of action (including finance, energy, mobility, economy, law and climate) into an integrated concept for the social-ecological transformation of the EU to reach carbon neutrality in 2050. Besides several other strategies and essential steps, the European Commission adopted the new EU Adaptation Strategy in 2021, based on the context of the Green Deal, which targets adaptation to climate change impacts and becoming climate resilient by 2050 (EC 2021). The Strategy aims to enhance the adaptation process, the cross-cutting themes: integrating adaptation into macro-fiscal policy, nature-based solutions for adaptation and local adaptation action (EC 2021). Furthermore, with the focus on citizen empowerment, knowledge sharing, learning and implementing solutions, the EU initiative Climate Pact was founded in 2020 (EC 2020).

2.2.4 Germany

Embedded in the international processes, climate adaptation and climate resilience have been gaining in importance in Germany since 1992, firstly through government-funded research into climate impacts and possibilities of climate change adaptation. After several negotiations and efforts in 2006, an essential step was undertaken by implementing the competence centre climate impacts and adaptation (KomPass) within the Federal Environment Agency (UBA). Based on these developments, in 2008, the first German adaptation strategy (DAS) entered into force (BMU 2020). The DAS builds a cross-sectoral policy framework for adaptation to climate change in Germany and includes regular monitoring (every four years). In addition, the DAS is updated and adjusted every five years. In order to realise the developed adaptation strategy, the German adaptation action plan (APA) was implemented for the first time in 2011. The APA contains the direct measures and activities funded and implemented by the federal government (e.g. research projects, implementations in spatial planning etc.) (BMUB 2015). The DAS and APA are the backbones of climate change adaptation in Germany as they aim to reduce the climate vulnerability of ecological, social and economic systems by simultaneously increasing the adaptive capacity of these systems (BMU 2020). Nevertheless, as well as the UN and the EU regulations, the national level sets the framework and mostly has a coordinating and informing function.

An essential instrument to enhance implementation at regional and municipal level are the Building Regulations. Therefore, besides the DAS, climate adaptation and climate resilience are also implemented in the *Baugesetzbuch* (the Federal Building Code "BauGB") and the *Raumordnungsgesetz* (the Federal Regional Planning Act, "ROG"). In section 2 (2) ROG, climate mitigation and adaptation are included as principles of spatial planning. Moreover, in 2011 the so-called "climate protection clause" was included in section 1a (5) BauGB: "The requirements of climate protection shall be taken into account both by measures that counteract climate change and by those that serve to adapt to climate change." Additional climate adaptation and mitigation are also included in the urban development funding Section 171 BauGB, Stadtumbau. Even though climate adaptation should have been taken into account in the planning process since 2011, Huber and Dunst (2021:513) found in their empirical research that climate adaptation measures are by far not considered in land use plans and development plans possible extent. This reflects missing awareness and political willingness regarding climate change adaptation. It remains to be seen how the German government, newly elected in 2021 and which has included climate resilience in its coalition agreement, will contribute to the further development of an integrative implementation and transformation process.

2.2.5 Climate policy and the importance of the local scale

By reflecting on the previous chapters above, it became apparent that lengthy negotiations, due to diverging national or political interests, unresolved financing, and less implementation willingness, etc., protract the international as well as the national policy process. The summaries and reviews by the IPCC have been disclosing the scientific discourse on climate change and its effects since the panel's establishment more than 30 years ago. As part of its First Assessment Report, the IPCC underlined the consequences of climate change and the need for adaptation strategies with its call to action: "The potentially serious consequences of climate change on the global environment give sufficient reasons to begin by adopting response strategies that can be justified immediately, even in the face of significant uncertainties," (IPCC 1992:118) and the necessity of an integrative mitigation and adaptation approach (IPCC 1992:118). The Kyoto Protocol, the first declaration regarding GHG reduction, was agreed seven years later (1997), but the first commitment period was between 2008 and 2012 – 18 years after the First Assessment Report and reflected the lengthy processes at UN level. Furthermore, as pointed out above, further declarations were made, but very few have been binding documents – e.g. Paris Agreement (2015).

As well as on the international level, the interrelated climate policy in the EU firstly focused on the reduction of GHG (Oberthür, Kelly 2008) and neglected the essential pillar of adaptation (Rayner, Jordan 2010). However, this fact changed in the 2000s, possibly also influenced by the Third Assessment Report of the IPCC published in 2001, which highlighted the importance of climate adaptation for both the Global North and the Global South (Rayner, Jordan 2010:147). Furthermore, with the following implementation of the Green and White Papers of the EU, the Adaptation Strategy in 2013, the European Green Deal and additional climate policy related regional programmes (e.g. for the Baltic Sea Region), the EU enhanced its processes dramatically.

Nevertheless, these negotiations and agreements are essential for the international guidance of climate adaptation and sustainable development. The agreements provide a broader framework and shared goals for the implementation on a national, regional and, especially, local scale. However, translating the agreements and policies into feasible measures is carried out on these scales, particulary the local and lower scales. Consequently, the vital role of local scales for the implementation process of adaptation and resilience gets conspicious.

Since international processes are prolonged, and actors on the local scale are already under pressure to adapt and enhance resilience, city networks like C40 Cities Climate Leadership Group (97 cities worldwide) (C40 Cities 2022), ICLEI Local Governments for Sustainability (over 2500 municipalities and regional governments worldwide) (ICLEI 2022), 100 Resilient City Network (The Rockefeller Foundation 2020) are essential stakeholders and actors within the implementation process.

Reconsidering the climate policies and the different levels, it is essential to mention that the goals for UN, EU and national level are tracked by monitoring processes. However, these measurements address only the respective scale. Therefore, the policy institutions can track the progress of adaptation and resilience building. Unfortunately, they do not support the local authorities and change agents by providing a level-integrating monitoring process and indicators suitable for lower scales and cannot be used as formative tools. For example, monitoring regarding the national adaptation strategy is implemented within the DAS. This monitoring is based on secondary, empirical data and includes 105 indicators. Fifty-six indicators focus on climate change impacts and 44 indicators measure activities and conditions supporting the adaptation process (BMU 2020). Besides the number of indicators being too high for the municipalities, due to the capacities and resources in the municipalities, the indicators provided are not conducive to the implementation process. Although, as mentioned in the previous sections, local actors are the most active players in the *Race to Resilience*, these levels are often neglected in previous approaches.

2.3 Climate-resilient pathways, decision-making and its challenges in the context of climate change

In its Fifth Assessment Report, the IPCC (2014) introduced and discussed the concept of climate-resilient pathways. It defined them as "development trajectories of combined mitigation and adaptation to realize the goal of sustainable development that help avoid ‘dangerous anthropogenic interference with the climate system'" (IPCCC 2014:1107). This anthropogenic interference is underlined by the concept of the Anthropocene, widespread by Crutzen and Stroemer in 2000. In this concept, humanity is identified as the dominant driving force of the planet. In further developments of this approach, the Anthropocene is further characterised by hyper-connectivity and complexity, as well as the high potential of destabilising the earth system (e.g. Leach et al. 2018:1-2). Furthermore, humanity needs to be considered as part of the biosphere and is not independent of the biosphere and vice versa. If humanity is the dominant driving force, humanity also can change societies' pathways.

Accordingly, climate-resilient pathways are not an outcome of a process; instead, they can be characterised as "iterative processes for managing change within complex systems, where unintended consequences are common owing to feedbacks, teleconnections, cross-scale linkages, thresholds, and nonlinear effects" (IPCC 2014:1112). To navigate these trajectories within a secure, adaptive space, implementing institutional strategies and decisions for risk management is essential (IPCC 2014:1106). Consequently, ongoing iterative knowledge creation, especially the assessment, and whether the implemented actions and decisions lead towards a climate-resilient pathway are crucial for ongoing foundational decision-making processes (see Figure 4).

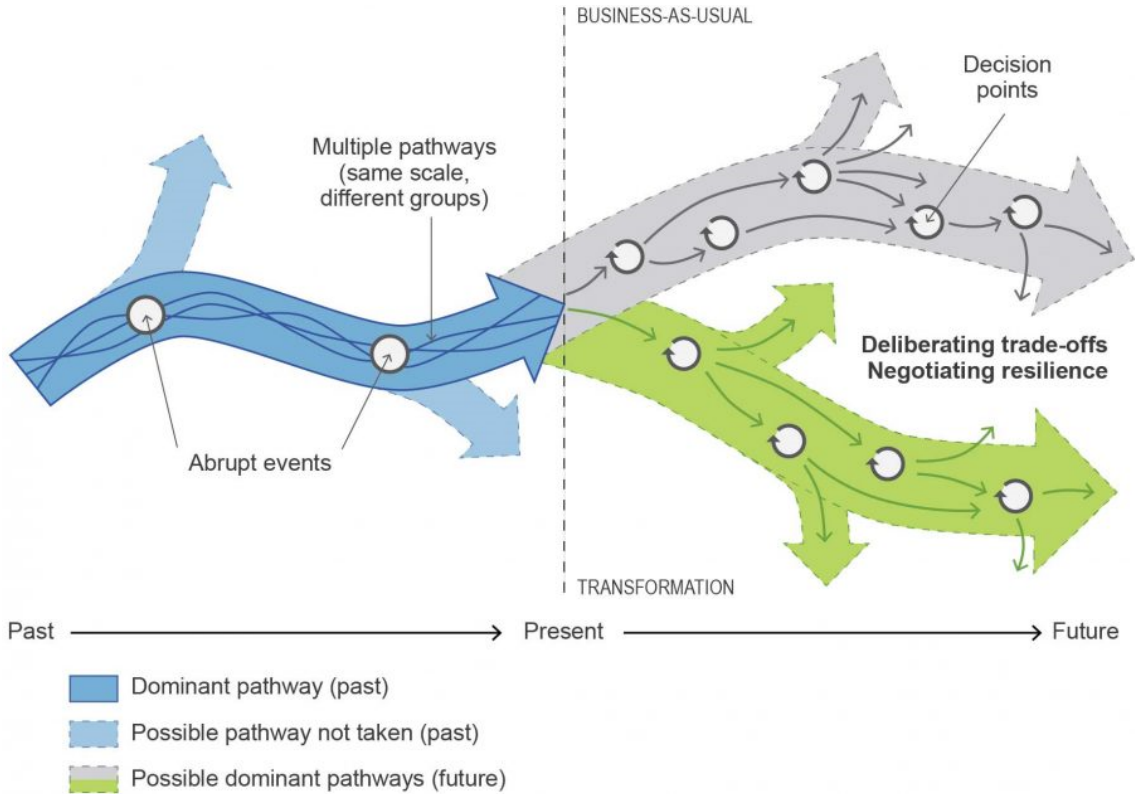


Figure 4: Schema of future pathways. Pathways into the future, with path dependencies and iterative problem-solving and decision-making. Source: Roy et al. 2018:469 acc. to Fazey et al., 2016:31

Embedded in the context of the Anthropocene, which Folke et al. (2021:837) emphasise as "characterised by a tightly interconnected world operating at high speeds and hyper-efficiency in several dimensions", managing these processes is complex due to multiple challenges. On the one hand, there are uncertainties about the exact impacts of climate change regarding the time of occurrence and their intensity. On the other hand, the highly interconnected social-ecological system itself is difficult to understand due to multiple feedback processes and the embeddedness of multiple scales (global, national, regional, local, individual, etc.) and subsystems, e.g. political, socio-economical, governmental, cultural and other social-ecological subsystems.

In addition to the acceleration of climate change, the acceleration of social change is also a central challenge for the management of climate-resilient pathways. As mentioned above, one characteristic of the Anthropocene is the interconnectedness and the high pace within systems. Hartmut Rosa's concept of "acceleration", as well as the concept "shrinking of the present" according to Lübbe (1992), can help to understand these circumstances. Rosa (2003) divides "acceleration" into the three areas of technological acceleration, acceleration of social change and acceleration of the pace of life, and declares a society to be an "acceleration society" if the three processes occur concurrently. Within an acceleration society, the "present of action [...] cannot shape this future because of the dynamics, the risks and the unmanageable amount of simultaneity within the present, which it cannot control at all" (Nassehi 2008, p.342; cited in Rosa 2003). Lübbe (1992) uses the term "shrinking of the present" to verbalise the phenomenon of a decreasing period of time in which knowledge and experience are valuable for the present and the future. Additionally, in each moment in which no climate-positive decisions are made, climate change accelerates further, and the impacts of climate change are getting more unpredictable. Therefore, decision-making is also under time pressure.

Reflecting on these concepts in the context of governing climate-resilient pathways, the requirements regarding knowledge, descion-making processes, and, therefore, governance are accentuated. In an accelerated world, circumstances are constantly changing in a concise time period, and the complexity and interrelation of dynamics and risks within and between social-ecological systems are intimidating (Masterson et al. 2019). Everything – climate change, social change, technology knowledge, experiences - is evolving rapidly. However, decisions need to be made to steer the climate-resilient pathways in this race. Decisions should be made in awareness of the high amount of uncertainty and need to be balanced all-time against different timescales (short, medium and long-term), new findings and new circumstances. Therefore, these decisions should be understood as consciously evolving decisions.

Nevertheless, it is crucial to keep in mind that climate change adaptation measures in particular are often decisions, which develop their full impacts on the environmental system after many years, such as the implementation of tree trenches and associated unsealing of parts of a road will achieve its full potential, once the trees are fully grown. Obviously, an adaptation measure should not be understood as a single decision but as a construct of multiple decisions, e.g. deciding which street will be unsealed, who is involved, which tree type will be used, etc. Each of these decisions has the potential to continue aloung the track of the climate-resilient pathways or to deviate from the path.

When considering the discussed elements, it is essential for concepts, tools and practices to be developed to adapt the accelerations and deal with risks, simultaneity, and uncertainty in steering the pathway towards a climate-resilient and sustainable future. Therefore, monitoring and evaluation are vital for visualising the impacts on different scales (spatially and temporally) and supporting the decision processes in uncertain circumstances.

2.4 Exploring resilience

The term "resilience" has gained increasingly in importance in science as well as in society. The concept is applied in various fields and disciplines and with different scopes. Hence, the definitions became more sophisticated and broadened. During recent decades, the concept became essential in its usage in ecology, psychology and engineering as well as in spatial planning, geography, governance or disaster management (Bulkeley, Tuts 2013; Davoudi et al. 2013; Leichenko 2011; Wardekker et al. 2020). Concerning climate change adaptation and disaster risk reduction, the resilience concept gained popularity and has become central since the 1980s (Béné et al. 2017:3).

As the concept is comprehensive, an approach to this term and its understanding in this thesis is elementary. Resilience can essentially be split into three basic understandings of resilience: engineering, ecological and evolutionary resilience. Engineering resilience derives from the constituent work of C.S. Holling in 1973, who was the first to define resilience within an ecological context. He characterises resilience as a systems property "that is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables." (Holling 1973, p. 14). Therefore, in the understanding of engineering resilience, a resilient system has the ability to return, or *bounce back*, to its original state of equilibrium after a disturbance (Davoudi et al. 2013).

Ecological resilience is also based on the work of Holling (1973), where he suggests that "resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist" (Holling, 1973, p. 17). In contrast to engineering resilience, ecological resilience systems can flip to another equilibrium, *bounce forward*, compared to the original one.

Evolutionary resilience overcomes the idea of stable states in which systems bounce back (engineering resilience) or bounce forward (ecological resilience). Therefore, the evolutionary understanding of resilience originates from social-ecological approaches to resilience and is referred to synonymously as social-ecological resilience. The social-ecological system perspective overcomes the socially constructed dichotomy of humans and the environment, and converges and integrates them into *one* human-environment system (Biermann 2021, p. 61). In this approach, the interactions between humans and the environment are brought to the forefront, and the social system is seen as an integral part of the ecosystem (Berkes 2017). Biermann (2021:63) emphasises that the social-ecological perspective breaks down the barriers between people and their environment and integrates them into a complex understanding in which agency is diffuse, interactions are dynamic, and system boundaries are blurred. Overcoming the dichotomous view is essential if the complex challenges are to be met.

The evolutionary resilience approach was firstly introduced in the late 90s (Walker et al. 2002; Walker et al. 2004:4). Folke et al. (2010:3) characterized it as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure and feedbacks, and therefore identity, that is, the capacity to change in order to maintain the same identity". Hence, in this understanding, resilience focuses on the capacities of an entity (such as a system, a community or an individual person) to maintain its individual identity while undergoing change (Böschen et al. 2017:217). Changes can be abrupt (like a hazard) and gradual (e.g. climate change) (Böschen et al. 2017).

The social-ecological (=evolutionary) resilience approach is applied in this paper. In general, resilience is understood here as a dynamic, relational process without a final status of the social-ecological system. For detailed summaries and reviews of the development of the resilience concept see Chelleri 2012; Bene et al. 2017; Folke 2006:260; Folke 2016.

2.4.1 Specific and general resilience

Beyond the different resilience concepts, it is also essential to differentiate between general and specific resilience. Most studies and research apply resilience to particular threats or aspects of a specific system or subsystem (Folke et al. 2010:4). One example would be examining the specific resilience of a coastal community against flooding. Therefore, specific resilience always asks "Resilience for whom?" and "Resilience for what?". In addition, though, the highly reciprocal characteristics of social-ecological systems (Folke 2006:262) need to be considered. Carpenter et al. (2001:767) emphasise in this context that "the history of human cultural evolution has been the story of cross-scale subsidies". This observation accentuates that the resilience of one system, subsystem or individual can also limit the resilience of another subject or system. When applied to the urban system, this implies, for example, that the additional development of a source to ensure drinking water supply can lead to another city having less water available. Consequently, negotiation processes and the consideration of conflicting goals between and within systems are of great importance.

In contrast to specific resilience, general resilience does not focus on one kind of threat or one subsystem. Instead, it focuses on coping with uncertainties in any way (Folke et al. 2010:5). Therefore, general resilience is essentially supposed to be open-minded and aware of the multiscalar effects within and between intertwined social-ecological systems. Nevertheless, general resilience is difficult to assess.

2.4.2 Resilience thinking

Resilience can be both (1) a systems property and (2) an approach for analysing and managing social-ecological transformation. In the previous chapters, resilience was described as a system's property. Hereinafter, resilience will be discussed as a framework for analysis and management, i.e. resilience thinking. It is evident that resilience is a concept that demands and enforces a systemic way of thinking, in which it assumes system properties and cross-scale dynamics and interactions (Walker et al., 2004; Béné et al. 2017:13). With resilience thinking, a framework is developed which focuses on the development and dynamics of resilient social-ecological systems as analysing and managing approach (Folke et al. 2010:1). Three aspects are central to resilience thinking: resilience as persistence, adaptability and transformability (Folke et al. 2010). Within the framework of resilience thinking, *resilience* is understood as the tendency of a system to remain within the current trajectory, even as it is constantly changing and adapting (Folke et al. 2010:6). The aspect of *adaptability* is defined by Folke et al. (2010:6) as "the capacity … to adjust its responses to changing external drivers and internal processes and thereby allow […] development within the current stability, […]."

Furthermore, *transformability* describes the capacity to overcome the current development trajectory entering a new pathway (Folke et al. 2010:6). The aspect of entering a new pathway underlines the innovative and novel character of transformation (Folke et al. 2010:7). Transformations address the general resilience of a system and are therefore influenced by multiple temporal and spatial scales and their interconnectedness. In a resilient social-ecological system, shock events can also lead to the opening of "windows of opportunities" and, building upon this, to transformation (Folke 2006:253).

Within the resilience thinking approach, it is apparent that all of these aspects need to be addressed simultaneously to develop resilient social-ecological systems, as they are interrelated, address different timescales and spheres of a system. Nevertheless, in practice, the capacities to adapt and transform are not often treated together (Elmqvist et al. 2019:271). Thus, in this thesis, resilience is understood as a dynamic, relational process without a final status of the social-ecological system.

2.4.3 Resilience as a (non-)normative concept

As Holling's definition from 1973 demonstrates, early definitions of resilience did not base the concept on a normative dimension (Béné et al. 2017:1). Systems or subsystems can contain resilient structures, leading to an increase in undesirable influences on society and ecology. Examples of this are invasive species or poverty structures (Dornelles et al. 2020:3). Therefore, resilience is understood initially as a non-normative concept.

In the meantime, resilience has increasingly become a central narrative for sustainable development. However, applied within the contexts of sustainable development and disaster risk reduction (e.g. Cutter et al. 2010), which are normative concepts, resilience includes the evolving and transformative character and embeds itself in current transformative processes in the sense of sustainable development. Therefore, the concept has increasingly received a normative connotation and is considered a quality that subjects (individuals, households, societies and cities) should acquire, especially against the backdrop of climate change and the resulting extreme events (Béné et al. 2017:1). Thus, the concept of (climate) resilience is established in this manner in international agreements such as UN Habitat III, the SDGs, the UNFCCC Paris Agreement and the Sendai Framework (see Chapter 2.2) (Wardekker et al. 2020) as well as in networks for increasing resilience, e.g. 100 Resilient Cities Foundation, the C40 and the ICLEI network. Accordingly, resilience is regarded as a normative concept and used as a goal of the adaptation and sustainable development processes in these contexts.

Consequently, even if the term resilience is broadly used as a normative concept, the possibilities of lock-in effects in resilient structures, e.g. forms of an autocratical system, as well as adverse reciprocal effects between systems, need to be incorporated.

2.5 Adapting to climate change

The previous chapters show how evident the intertwined character of climate resilience and adaptation is. Municipalities, cities, or local change agents are implementing adaptation measures to deal with actual or anticipated challenges of climate change and keep track of climate resilient pathways within a safe operating space.

In order to get a deeper understanding of adaptation, a definition of the terms *adaptation* and *adaptability* within the context of resilience is necessary. *Adaptation* is defined by the IPCC (2012:17) as "the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities". Adaptability or adaptive capacity, which are often used synonymously, is necessary to implement adaptation. *Adaptability/Adaptive capacity* is defined by Walker et al. (2004:7) in the context of SES as "the collective capacity of the human actors in the system to manage resilience". Existing adaptive capacity will not directly lead to adaptation (Berrang-Ford et al. 2011:25).

Even if societies and humankind have ever adapted to changing climate (Berrang-Ford et al. 2011:25), the current situation (Chapter 2.1) poses inherently new and fundamental challenges to the adaptation process. Embedding adaptation into the broad context of climate change became apparent that the impacts of climate change became unavoidable, and climate change adaptation turned out to be an essential strategy to reduce vulnerabilities and enhance climate resilience. Nevertheless, the relevance of climate change adaptation in climate policy has only been recognised since 2000 (see Chapter 2.2). Until 2000, climate mitigation was a primary objective in international policies; since then, climate adaptation has also gained importance (see Chapter 3.2). Adaptation within an SES takes place through different adapting actors (e.g. government, communities or individuals) with different adaptive capacities (Pelling 2011), on different scales (local to global) (Berrang-Ford et al. 2011:26) and through different actions. As adaptation measures are implemented within highly interdependent social-ecological systems, their effects and impacts affect the whole system, even to differing extents.

Considering this as a generic model of enhancing climate resilience, the status quo is first considered. Then, the identified lack of climate resilience leads to the design and implementation of a specific adaptation activity, which should lead to the enhancement of capacities of a system or entity, which finally improves the climate resilience of a system.

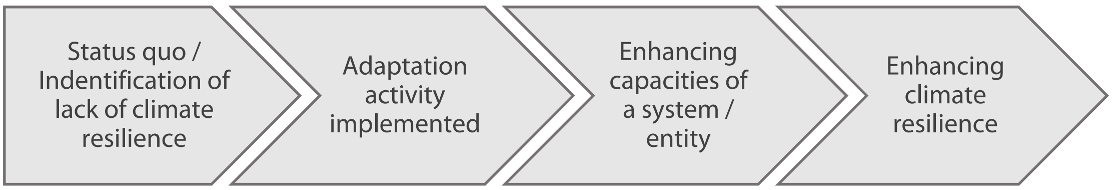


Figure 5: Generic theory of change of an adaptation intervention
Source: own figure according to Béné, Frankenberger et al. 2015

Therefore, climate change adaptation is essential for enhancing climate resilience and pushing sustainable social-ecological transformation forward. However, as well as the impacts of climate change being manifested at the local scale, adaptation measures are implemented at the local scale. Higher scales, e.g. the global scale with its international policies, give a frame and establish concepts on a global scale, but the local scale is ultimately responsible for implementing adaptation measurements. Therefore, it needs to be highlighted that the actors on the local scale are most important for the adaptation process as they perform the abilities of an urban system (Williams et al. 2015, Fischer, Newig 2016; Otto et al. 2020).

Even if adaptation actions are implemented on the local or lower scales, it is crucial to reflect them regarding their potential reciprocal effects on higher or lower scales, other dimensions of resilience and other parts of the social-ecological system to reduce potential maladaptation and enhance general resilience (see Chapter 2.4.1.) (Eriksen et al. 2011; Barnett, O'Neill 2010:211). The IPCC defines maladaptation as *"an adaptation that does not succeed in reducing vulnerability but increases it instead"* (IPCC, 2001, p.990). These maladaptive effects can also occur between different social-ecological systems or subsystems. For example, an adaptive activity that enhances one group's resilience can be maladaptive and reduces resilience for another group. Consequently, it is of great necessity and importance to recognise that: 1) not every type of adaptation measure is a good adaptation measure (Adger et al. 2011:7580; Barnett et al. 2010); and 2) considering adaptation measures in conjunction with sustainable development is vital to identify and avoid trade-offs (Eriksen et al. 2011; Dornelles et al. 2020:3). In order to examine maladaptation very early and enhance adaptation, monitoring and evaluation are needed.

2.6 Monitoring, evaluation and climate resilience

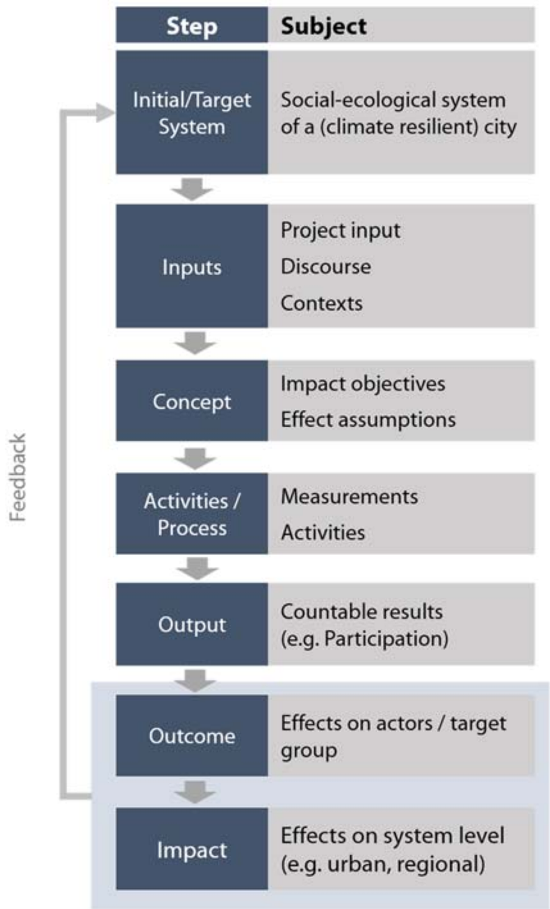
The chapters above point out the urgent need for navigating the highly complex process of resilience building and climate change adaptation. Monitoring and Evaluation (M&E) play a pivotal role in the transformation process to sustainable and resilient trajectories. M&E can enhance the understanding of resilience, adaptation action and its impacts on resilience. Furthermore, it enhances the management of the process, legitimacy and social enlightenment (Stockmann, Meyer 2016:40). Therefore, M&E are encouraging an ongoing improvement process through learning effects (Pringle 2011:5). Learning about the effectiveness of adaptation measures is crucial for a faster and more efficient transformation (Bellinson, Chu 2018; EEA 2020b:77, Stockmann, Meyer 2016).

Monitoring and evaluation are broad terms and are often used synonymously. In the following paragraph the key terms monitoring and evaluation, as well as the relevant forms of evaluation (formative and summative) relevant to this research and objectives of the evaluation are defined as follows:

- **Monitoring:** A systematic data collection ad of specific indicators which embodies the regular tracking of inputs, activities, outputs, outcomes and impacts of activities at the project, programme, sector, national levels, e.g. monitoring of country's progress against the Sustainable Development Goals (IEG 2022).

- **Evaluation:** Systematic assessment of an intervention, programme or policy (ongoing or completed) to determine the relevance and fulfilment of objectives, development efficiency, effectiveness, impact and sustainability and to enable the incorporation of lessons learned into the decision-making process (IEG 2022).
- **Formative Evaluation:** Takes place during an intervention in order to identify possibilities to improve and steer the intervention to achieve the desired outcomes. It is often associated with ex-ante and mid-term evaluations (Pringle 2011).
- **Summative Evaluation:** Is applied after a programme as ex-post evaluation and assesses the whole intervention regarding its effectiveness.
- **Objectives of Evaluation:** The target setting for evaluation can differ significantly. According to Weith (2018:627) there are four main functions of evaluation: controlling function, legitimisation function, dialogue/learning function, recognition function.

Figure 6: Logical model for climate change adaptation interventions



Source: own figure

As adaptation action takes place locally, the importance of M&E being applicable for local authorities or local adaptation projects is undeniable. However, few local authorities are currently using this crucial tool (EEA 2020b:119). In order to structure the M&E process, the development of a logic model is essential. The model draws upon similar concepts like the Logical Framework Approach (LFA) or the Theory of Change (ToC) (Pringle 2011:14), which is also applied often in development programmes (Béné et al. 2015). These concepts can be implemented during the development process of an intervention and within the monitoring and evaluation process. Furthermore, these models cut down the complexity of an intervention, programme or policy to a practical description of the process. The number of analytical steps' can differ due to the specific scope of an M&E process. However, the steps input, output, outcome and impact (see Figure 6) are implemented in most M&E processes (Brown et al. 2018).

As Pringle (2011) points out, a logical model can provide a tangible understanding of the intervention or process, which will be monitored and evaluated as the impact objectives, the activities for achievement, the planned target groups and the expected impacts on the target systems as well as the project resources etc. are defined. With a broad understanding of this model, and the intervention, it is possible to evaluate, e.g. the achievement of the planned outputs, outcomes and impacts (intervention's objectives). Therefore, the logical model forms the basis for the M&E process (Pringle 2011).

Figure 6 presents a developed logic model for adaptation measures within the resilience-building context. Firstly, the initial/target system should be defined (e.g. the social-ecological system of a climate-resilient city). Secondly, the inputs of the adaptation measure need to be defined. However, besides the financial and personal resources, influential discourses and contexts should be reflected ideally (e.g. the public and scientific discourse on climate resilience). The third step, concept, describes the intervention's impact objectives and effect assumptions. Fourthly, activities/process should be defined (e.g. specific participatory methods). Output assesses the countable results (e.g. number of participants, number of website views, number of information materials), whereas the outcomes reflect the (mid-term) effects on the target groups. Impacts are the long-term effects at system level (e.g. the social-ecological system of a climate-resilient city). Outcome and impact are both affecting the target system. In the presented research, the initial system functions as baseline against which the outcome and impact need to be measured.

In addition, Pringle (2011:26) noted that three possibilities of measuring are possible in terms of climate change adaptation and resilience: 1) against the objectives of the intervention, 2) against an emerging understanding of good adaptation, and 3) against baselines. The presented research focuses on measuring against the objectives of the intervention (reflecting the outcome and impact against the concept) and on measuring against baselines (outcome and impact against the baseline of the initial system).

To operationalise the M&E process, indicators are obligatory. In the context of climate resilience, the operationalisation of the concept is challenging (Asadzadeh et al. 2017:147). Additionally, due to complex systemic interactions, resilience and adaptation must be measured by proxies (Tyler et al. 2016:421). In order to assess (climate) resilience and the success of adaptation strategies, which aim to enhance resilience, many different resilience-focused approaches were published (Schipper, Langston 2015).

Most resilience indicator sets focus on ecological, economic and socio-economic quantitative data (Bakkensen et al. 2017; Cutter et al. 2016; Tyler, Moench 2012; Wardekker et al. 2020), such as the Baseline Resilience Index for Communities (BRIC) of Cutter et al. (2010), the Community Disaster Resilience Index (CDRI) published by Peacock et al. (2010). Only few frameworks apply an integrated method approach by using qualitative methods both during framework development (primarily) and for assessment (Engle et al. 2014; Jones, Tanner 2015). The existing indicator sets assess resilience on different spatial scales: on district scale (e.g. Cutter et al. 2010), on the city scale (e.g. The Rockefeller Foundation 2014), on the community scale (e.g. Renschler et al. 2010), on the neighbourhood (Pfefferbaum et al. 2012) or at the household level (Jones, Tanner 2015; UNDP 2014). These indicator sets focus on only one scale, which neglects the multiscalar effects and impacts of adaptation action.

Although place-based community resilience has been mainstreamed already, the individual scale has not been addressed to the same extent (Otsuki et al. 2018). The existing resilience or disaster risk indicator sets on an individual – or household-specific – scale apply the sustainable livelihood approach (Béné et al. 2016a; Brown, Westaway 2011; Jones 2018; Vaitla et al. 2012) and tend to focus livelihood, social or community resilience (Speranza et al. 2014; Quandt 2018). Within these approaches, indicators regarding nutrition, agriculture and livelihood strategies are mostly used. Besides these measurement frameworks, a diverse range of approaches that focus on subjective resilience exists (Béné et al. 2016b).

In addition to the ecologically, economically and socio-economically oriented indicator sets, only a few approaches, such as the "embrace framework" by Kruse et al. 2017, address action and learning of communities, but primarily on the system level. The importance of measuring soft and actor-focused factors of improving the urban climate resilience – e.g. knowledge, behaviour, motivation and agency – is pointed out in different studies but addressed less actively in the evaluation and monitoring context (Cote, Nightingale 2012; Williams et al. 2015).

When reflecting on the elements of climate change, international policies, resilience and climate adaptation, which have been discussed, it became evident that especially the multiscalar aspect is missing within the current approaches. The approaches assess resilience and adaptation only on one scale and do not combine the measurements. Furthermore, the role of citizens as actors of change within the adaptation and transformation process to a resilient system has not been addressed to the same extent as pointed out above. Moreover, the neighbourhood or household scale frameworks are grounded in the sustainable livelihood approach, which is less suitable for measuring the global north, especially in Germany.

2.7 Conclusions of the state of the art

Climate change poses complex challenges to societies. The need for action to enhance climate resilience and adapt to climate change's unavoidable impacts is unequivocal. International policies frame the development of climate-resilient pathways in the Anthropocene. However, international negotiations are tedious. Nevertheless, local actors already face the impacts of climate change or anticipate it, and they are forced to act as climate change is a global phenomenon but triggered through local action. Therefore, the action for adaptation and resilience-building also needs to be conducted on the local scale. Hence, the role of local action, especially in cities, is essential for the transformation process towards climate resilience. Cities and city networks, which proactively address the place-specific impacts, vulnerabilities and challenges of climate change, and climate resilience, are crucial for sustainable resilience building and global climate action.

Nevertheless, these cities and change agents face the complexity of context specificity – e.g. specific vulnerabilities, socio-economic factors, culture, social cohesion – and the multidimensional and multiscalar characteristics of climate change and resilience. Additionally, the spatio-temporal decoupling of action and effect and the unpredictable extent of climate change impacts is challenging regarding the impact assessment of adaptation action and the public discourse within the cities. Finally, the acceleration of the pace of time, social change, and climate change reduces the time horizon in which decisions can be made.

Monitoring and evaluation are crucial for navigating the transformation process towards sustainable and resilient cities and would be highly beneficial within the transformation. First, M&E provide regular feedback and build up an evidence base. Thus, maladaptation can potentially be recognized as early as possible, enhancing learning effects and a positive adaptation process (Bellinson, Chu 2018). Further, M&E contributes to transparency and accountability of adaptation actions and tangibly increases climate resilience and adaptation for decision-makers and policy-makers.

3 Methodology

"As for the future,
your task is not to foresee it,
but to enable it."
Antoine de Saint-Exupéry 1948

To enable the future, this paper focuses on assessing climate resilience and climate adaptation measurements aiming to shape climate-resilient development pathways on the local scale. Therefore, monitoring climate resilience and evaluating climate adaptation processes are central approaches in this thesis. The aim is to develop a validated, cross-scale, integrating monitoring and evaluation approach for climate resilience and adaptation to build a scientific foundation for the practical application, e.g. within local interventions or local governments.

The research herein is based on a sequential mixed-methods design, predicated on data generated in the research project MONARES. The research project MONARES "**Mon**itoring of **A**daptation Measures and Climate **Res**ilience in Cities", was funded by the Federal Ministry of Education and Research (BMBF) for three years between 2017 and 2020. MONARES was designed as accompanying research and thus supported 14 funded research projects with the BMBF research focus, "Climate resilience through action in cities and regions". In addition to developing an urban climate resilience framework and indicators, the central objectives were to support the 14 funded research projects regarding monitoring and evaluation.

The research projects, which implemented climate change adaptation measures throughout Germany, had diverse foci. They differed in terms of stressors (e.g. heat, droughts, heavy rain, floods, storms), target groups (including civil society, administration and politics) and spatial scale (e.g. street, neighbourhood, district). Furthermore, the projects also varied in how the measures were implemented and thus in the methods applied. However, the adaptation to climate change of the urban social-ecological system could be identified as a common objective. In addition, raising awareness and changing the actors' behaviour are goals emphasised in each project. In Chapters 3.2 and 3.3, two projects of the "Zukunftsstadt" [Future City] initiative are presented as examples to give an impression of the cooperating projects within the funding programme.

3.1 Methodological overview

The foundation for answering the research questions was a literature review. The results of RQ/IL/a,b, RQ/SL/a and RQ/AL/a (see Figure 7) are based on data and surveys generated within the MONARES research project. Within MONARES, an explorative preliminary study, a total of three online surveys and two expert workshops for data collection were conducted. For RQ/SL/b, secondary statistical data was used (see Contribution 2 – Appendix C). The respective detailed methodologies are presented in the papers (see Appendix B, C, D). Hereinafter a brief overview of the methodology, which is relevant for the study, within MONARES is given. It is important to mention, that the whole research process of MONARES was developed as a co-creational process by an iterative design between the MONARES consortium and the cooperating research projects.

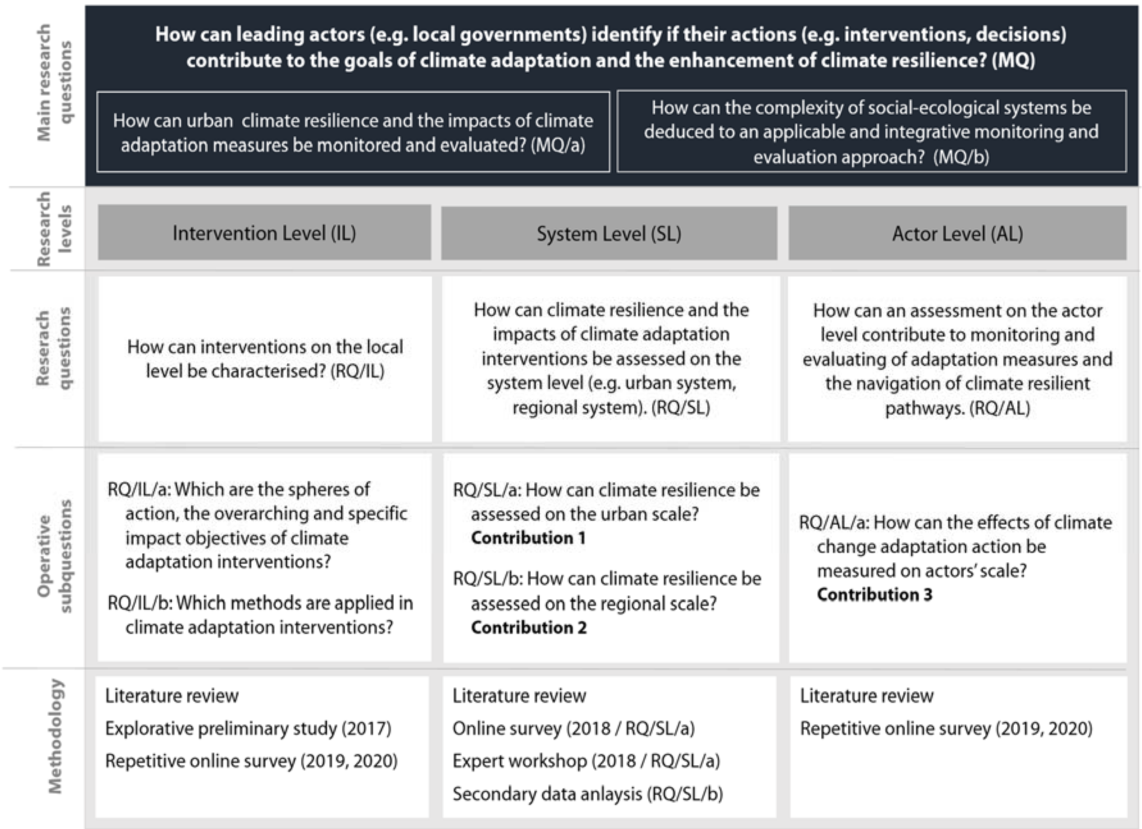


Figure 7: Research structure, questions and methodology
Source: own figure

Explorative Preliminary Study (2017): To gain a deeper understanding of the projects' research approaches and aims, an explorative preliminary study was conducted at the start of MONARES. The questionnaire with open questions was sent to the cooperating adaptation projects and answered in written form by the respective project leader. All 14 projects participated and answered this survey. This pre-study aimed to get initial impressions about:

- Which stressors do the projects mainly deal with?
- Which measures will be carried out in the projects?
- Which methodologies will be applied?
- Which target group will be addressed?
- On which spatial level will the project work?

This preliminary study was analysed using MaxQDA and served as a basis for constructing the repetitive online survey

Online survey – Urban Resilience Indicators (2018): After the development of a resilience framework, a literature review and a first process of indicator development (see Appendix B– Contribution 1), an online survey was conducted. The survey was implemented to validate and reduce the indicator-set by empirical data and to use the expert knowledge of the cooperation projects. The first online survey (n=39) focused on the expert rating of the developed indicators (see Appendix B– Contribution 1). The project staff were asked to rate the potential indicators (e.g. degree of soil sealing, wetlands and retention areas, innovation Index, accessibility of hospitals) based on the literature review regarding how they assess them for monitoring climate resilience in urban areas (see Appendix B– Contribution 1).

Expert workshop on urban resilience indicators (2018): To consolidate the interdisciplinary knowledge and experiences on urban climate resilience, and validate the indicators by experts, an expert workshop was held. At the expert workshop (n=20), the online survey evaluation was presented. The results of the online survey and each indicator were discussed in focus groups and consolidated in plenum. Using the workshop results, the indicator set was revised and finalised (see Appendix B– Contribution 1).

Repetitive online survey (2019, 2020): To address the monitoring and evaluation development as well as the empirical validation of actor-focused indicators, a repetitive online survey was conducted focusing the intervention level and the actors' level. The survey was developed based on the preliminary study results and the findings from the previous surveys and workshops, and the literature review. The survey was divided into four parts and focal points: 1) Survey of the impact spheres and impact goals of the projects (RQ/IL/a); 2) Survey of the methods used in the projects (RQ/IL/b); 3) Concept of climate resilience (RQ/IL); 4) Self-assessment of knowledge and action concerning climate resilience (RQ/AL/a). Part 3) and 4) in particular, were designed with an exploratory character to empirically validate the indicators for knowledge and behavioural changes. The survey was conducted in 2019 (n=59) and 2020 (n=53) as a trend study (see Table 2). The online survey was sent to the cooperating projects of the *Zukunftsstadt* initiative, and it was explicitly pointed out that the practice partners of the consortia could also participate in the study. The survey was analysed using SPSS and Excel (see Appendix D– Contribution 3).

Table 2: Overview of study sample 2019 and 2020

		Gender				Profession			
Year	n	Female	Male	Diverse	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

Source: own table

3.2 Presentation of exemplary projects

The cooperating projects in the *Zukunftsstadt* funding programme were all focusing in enhancing climate resilience through action. Nevertheless, their approaches are very varied. To get an impression of the projects, two are exemplarily characterised in the following paragraphs.

Example 1: Grüne Finger Osnabrück

The project "Produktiv. Nachhaltig. Lebendig. Grüne Finger für eine klimaresiliente Stadt" [Productive. Sustainable. Vibrant. Green fingers for a climate-resilient city] – from now on referred to as *Grüne Finger* [Green Fingers] – operates on a city-wide level in Osnabrück.

Stressors: The focus is mainly on the stressors of heat, heavy rainfall and flooding.

Problem: The land- and cityscape of Osnabrück are characterised by the *Grüne Finger*, which radially extends into the cityscape with its green and open spaces (Grüne Finger 2021). The function and usage of and in the *Grüne Finger* are very diverse and multidimensional. For example, these open spaces provide central urban climatic services by ensuring and enabling the supply of fresh air. In addition, the *Grüne Finger* contribute to water storage and the absorption of water during heavy rain and flooding events. Another function of the *Grüne Finger* is its use as agricultural and forestry land (Grüne Finger 2021). In addition to the ecosystem services already mentioned, the *Grüne Finger* also provide space for local recreation.

Moreover, the *Grüne Finger* give the city of Osnabrück contour and structure, thus making a central contribution to socio-cultural aspects, e.g. increasing consumer-producer relationships reconnecting urban people with life-support systems in the city (Schulz et al. 2019; DStGB, Difu 2022). However, the *Grüne Finger* are not recognised as a coherent open space system and are not protected despite their central importance. Therefore, they are subject to conflict with settlement pressure and other competing uses (Dressler 2021; DStGB, Difu 2022).

Objectives: The *Grüne Finger* project deals with the issues presented above, carries out a spatial analysis, and draws up a development concept. In particular, it aims to raise awareness of the importance of the *Grüne Finger*, integrate the results of participatory measures into policy and thus ensure the preservation and strengthening of the climate-relevant open space function of the *Grüne Finger* in the medium term. In addition, changed agricultural concepts, for example, are also identified as an impact objective of the *Grüne Finger* project. Thus, on the one hand, a socio-cultural change in the region is promoted and, on the other hand, a change in the way the region is managed (Grüne Finger 2021; DStGB, Difu 2022).

The objectives are to be achieved through various creative participation formats, such as perception workshops in the *Grüne Finger*, art activities, walks and workshops. In addition, an intensive integration of politics and important stakeholder groups – citizens' advisory councils and key groups of people – is planned (Grüne Finger 2021;).

Example 2: GoingVis

The joint project "GoingVis – Mit kühlem Kopf in heißen Zeiten" [GoingVis – Keeping a cool head in hot times] works on a city-wide level in small Eastern German towns (Boizenburg, Uebigau-Wahrenbrück, Bad Liebenwerda) and focuses on adaptation to the stressor heat (DStGB, Difu 2022).

Stressor: Heat

Problem: Technological and planning measures are often at the centre of climate adaptation strategies. Moreover, many of these measures are implemented in large cities. Nevertheless, small towns and smaller municipalities also face the major challenges of climate change. In contrast to large cities, they usually do not have the necessary human and financial resources to implement costly structural measures. *GoingVis* identifies social and behavioural measures in particular as the core for successful climate adaptation, both for large and small cities (DStGB, Difu 2022).

Objective: *GoingVis* aims to disclose visions of the future and the development and testing of ideas for common adaptation practices concerning the stressor heat in the small towns of Boizenburg, Uebigau-Wahrenbrück and Bad Liebenwerda. The visions of a climate-adapted future are developed in an integrative, inclusive and iterative process with the citizens and actors in the towns. Central to this approach is, on the one hand, the participation of vulnerable groups as well as groups that have not been involved to date and, on the other hand, the focus on identity-forming spaces and places in the cities during the process. In the medium term, this should increase the adaptive capacity of the population and thus of the cities (DStGB, Difu 2022).

4 Results and brief introduction of the contributions

The following section briefly presents the empirical results and the peer-reviewed and published contributions. Finally, the results are concluded into an integrative, multiscalar monitoring and evaluation concept.

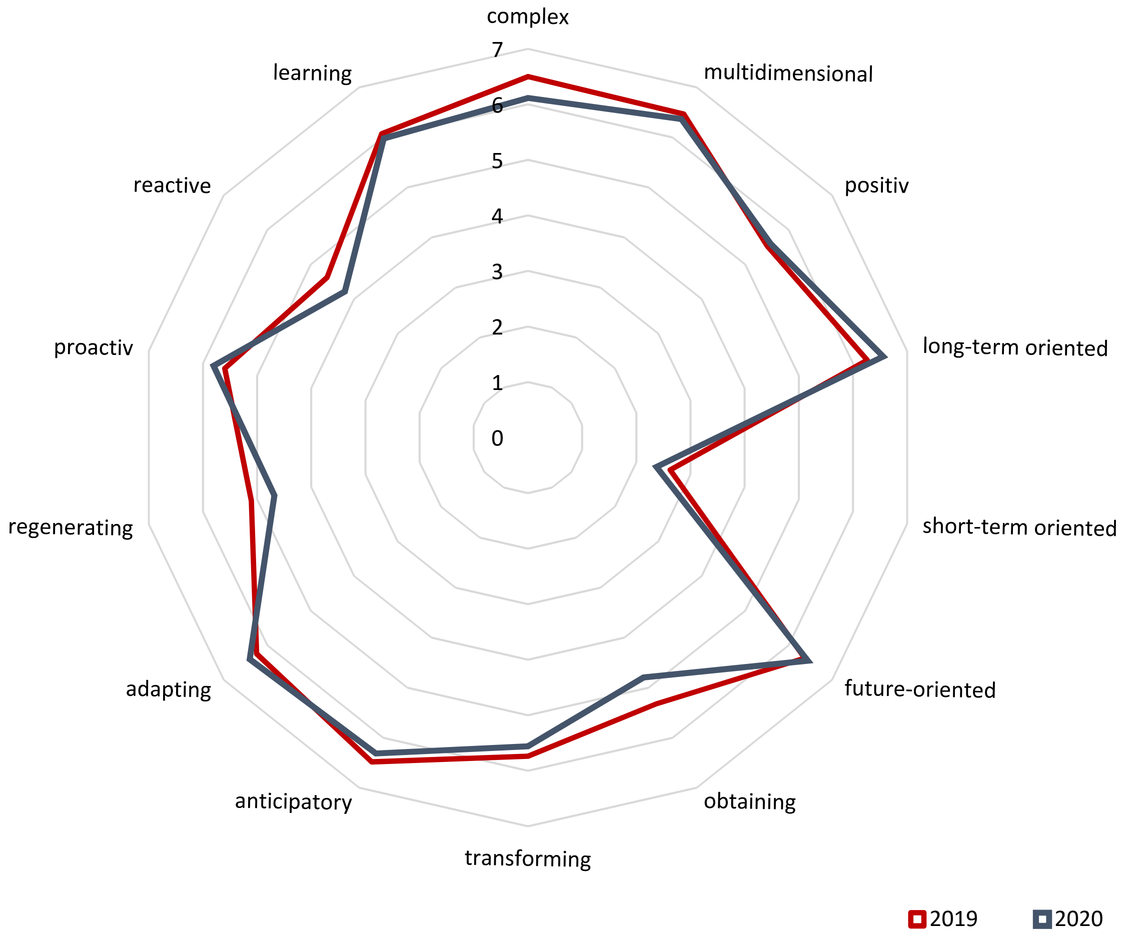
The section is structured into three main parts. These parts are oriented towards the three research levels presented in Chapter 3.3 – Intervention level (Chapter 4.1), System-level (Chapter 4.2) and Actor level (Chapter 4.3). Chapter 4.1 gives empirical insights into the cooperating projects' interventions within "Zukunftsstadt" funding programme of the BMBF. Chapter 4.2 deals with the system level and is divided into the urban scale (Chapter 4.2.1) and the regional scale (Chapter 4.2.2). Within these two chapters, brief summaries of the published articles "**Indicators for Monitoring Urban Climate Change Resilience and Adaptation"** (Chapter 4.2.1) and "**Regional climate resilience index: A novel multimethod comparative approach for indicator development, empirical validation and implementation"** (Chapter 4.2.2) are presented. Chapter 4.3 deals with the actor level and summarises the published article **"Measuring knowledge and action changes in the light of urban climate resilience".** Finally, in the last subchapter (Chapter 4.4), the integrated monitoring and evaluation approach is presented and discussed.

4.1 Intervention level: Empirical insights from the cooperating projects

In order to get a deeper understanding of the study sample, the empirical results of the repetitive online surveys from 2019 and 2020 are presented in the subsequent paragraphs – the overall sample of 2019 consists of 59 respondents. In 2020, 53 persons replied to the survey (see Table 2). The complete survey, which was in originally in German, can be found as supplementary material in Appendix E. Therefore, the survey questions are not repeated verbatim in the following sections.

Before presenting the results regarding the impact spheres, impact objectives and applied methods, it is important to take a look at the perception of the resilience concept within the projects. As resilience is a broad concept, it was necessary to gain insight into the understanding of the concept from the actors responsible for the climate adaptation projects. The empirical results of the survey underline the broad concept of the term resilience. The participants were asked to rate 14 attributes on a seven-point Likert scale in order to capture the personal perception of the term resilience. At both survey times, the survey results were very similar (see Figure 8). The mean of the attributes *complex, multidimensional, long-term oriented, future-oriented, anticipatory, adapting* and *learning* is rated over 6. This means that these attributes are important in the participants' understanding and are very likely to describe the characteristics of the term resilience. On the other hand, *short-term oriented* and *reactive* attributes got the lowest rates.

Figure 8: Personal perception of the term resilience of the project staff in 2019 and 2020. 0=not associated with resilience, 7=highy associated with resilience.



Source: own figure,

4.1.1 Impact spheres

As described in Chapter 3, the research projects had very diverse focal points. Therefore, to get a more precise understanding of the differences and commonalities of the projects, they were asked about their impact spheres and about their impact objectives (RQ/IL/b).

In Figure 9, the impact spheres in which the project actors locate their projects are presented. The focus of the projects, according to the participants, is on *Capacity Building, Management and*

Planning, Behavioural Change of Actors, Information and Communication, and *Green Infrastructure*. The impact sphere *Guidelines and Principles*, *Monitoring and Precautionary Systems*, and *Financing and Technology*, play a subordinate role among surveyed project members.

This result confirms the previous explorative study and can be well explained in connection with the funding priority in which the projects are to be located.

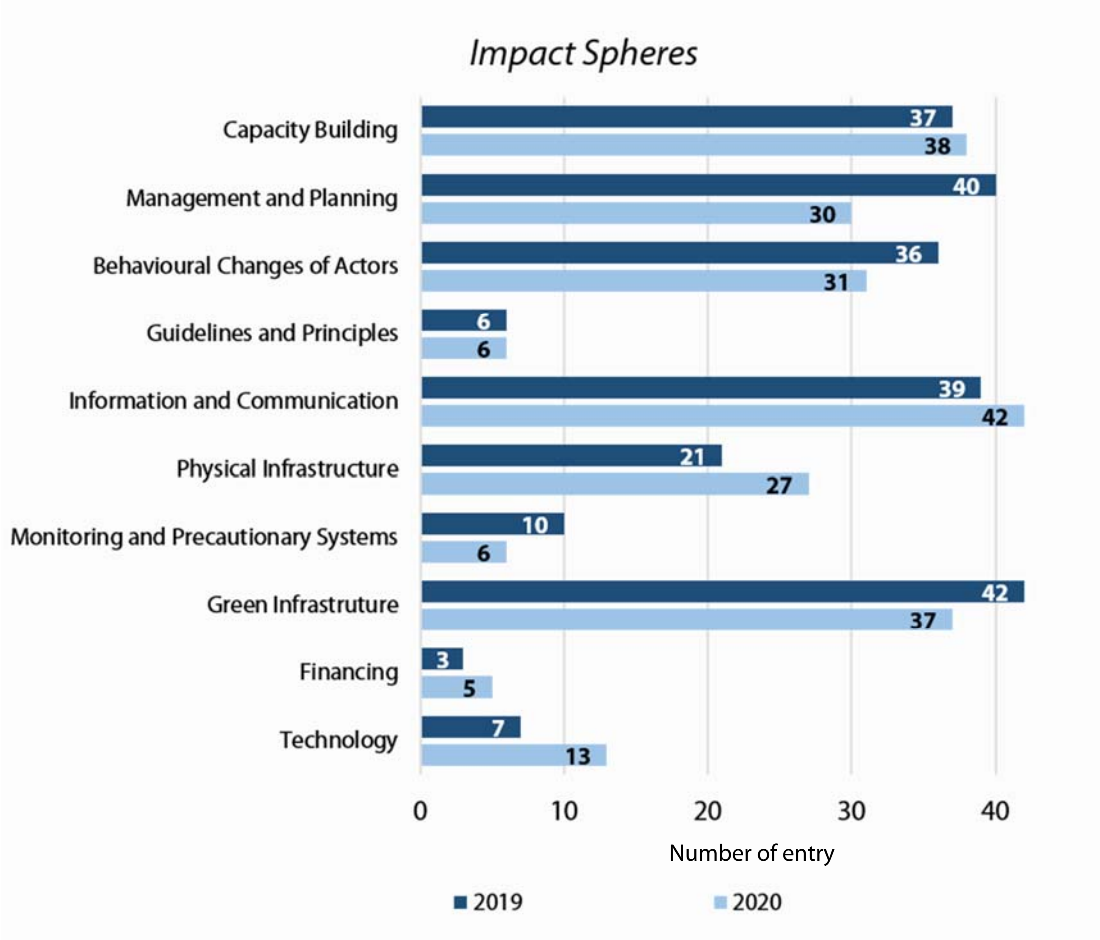


Figure 9: Impact spheres in which project actors locate their projects.
Source: own figure

4.1.2 Impact objectives

The subsequent paragraphs differentiate between overarching impact objectives and specific impact objectives (RQ/IL/c). All participants rated the overarching impact goals within the survey, whereas the specific impact objectives were selected through the impact spheres.

Overarching impact objectives

The study participants were asked to rate 15 overarching impact objectives, which were selected based on the exploratory pre-study. In addition, the respondents were asked to rate on a seven-point Likert scale between "very important" and "not at all important".

Many overarching impact objectives are reported as "very important" (Appendix - Table A1). The following impact objectives are in the focus of the projects:

- the development of long-term guiding principles
- transferable implementation measures
- integration of results into urban planning
- sensitisation and awareness-raising of actors regarding climate resilience
- improvement of communication between and with stakeholders
- improvement of quality of life
- improvement of environmental quality
- improvement of knowledge and information transfer between actors on the ground
- improvement of knowledge transfer between research and practice and
- further development of coping strategies for extreme events

As these impact objectives are all rated as "very important" the high target-heterogeneity of, and more importantly within, the research projects became apparent. In contrast, a subordinate relevance is found for impact goals that tend to be technically oriented, such as *improvement of energy efficiency, early detection of extreme events* and *improvement of resource efficiency.*

The very high ratings of the projects concerning the many impact goals indicate that the projects themselves are comprehensive in scope and always serve a wide range of impact goals. However, the wide dispersion of the stated overall objectives may also indicate that the objectives are either not clearly defined in the projects or are not communicated concretely enough within the projects. This may result in a situation where not all project members have the same understanding of the projects' impact objectives.

Specific impact objectives

Within the survey, the five highest-rated impact spheres were selected to take a closer look at their specific impact objectives. Firstly the specific impact objectives of the impact sphere Capacity Building are presented, followed by Management and Planning, Behavioural Changes of Actors and Information and Communication. Lastly, the specific impact objectives of the impact sphere Green Infrastructure are summarised.

Capacity Building

In 2019, 63% of the respondents and in 2020, 72% of the respondents indicated that their projects deal with the impact sphere of Capacity Building. All these respondents could rate the specific impact objective area of Capacity Building (Table 3). The impact objectives *activation and mobilisation of actors, development of decision-making aids approaches and recommendations for action, sensitisation* and *awareness-raising* are assessed as very important for the specific projects (see Appendix A - Table A2). Likewise, the *improvement of knowledge transfer* and *networking of actors* are identified as necessary. The impact goals *activation and mobilisation of actors* and *sensitisation and awareness-raising* also stand out due to their very low standard deviation. This means that these two impact goals, which reflect the empowerment concept, are considered very important in their projects by all project actors working in the field of capacity building.

Table 3: Possible specific impact objectives of the impact sphere Capacity Building.

Capacity Building	• Activation and mobilisation of actors • Development of counselling services for the respective target group • Development of decision-making aids approaches and recommendations for action • Sensitisation and awareness-raising	• Strengthening self-empowerment and self-regulation • Improvement of knowledge transfer • Networking of actors • Knowledge about coping strategies during extreme events

Source: own table

Management and Planning

In 2019, 66% of the participants and in 2020, 55% of the participants rated the impact sphere Management and Planning as necessary for their research project. The specific impact objectives

Table 4: Possible specific impact objectives of the impact sphere Management and Planning.

Management and Planning	• Development of decision-making aids, solution approaches and recommendations for action • Integration of the results into the urban development programm • Integration of the results into urban land use planning (Bauleitplanung) • Integration of the results into urban development funding	• Integration of the results into the urban framework planning (Städtebauliche Rahmenplanung) • Improving land provisioning & ensuring fresh air supply • Improve land use planning with regard to open spaces that are important for climate ecology. • Improving water retention & stormwater management

Source: own table

(Table 5) within this sphere are all rated as essential goals within the projects. Especially the goals *Development of decision-making aids, solution approaches and recommendations for action* and *Integration of the results into the city development programme* are graded as most important goals (see Appendix A - Table A3).

Behavioural Changes of Actors

In 2019, 63% of the respondents and 2020, 57% of respondents reported that their project is working in the impact sphere of *Behavioural Changes of Actors.* This group was then asked to rate the specific impact objectives (Table 5) within this sphere. *Activation and mobilisation of actors* and *Improvement of knowledge transfer between actors* and *Interconnecting actors* were rated most important than the other impact objectives. Also, the *Development of counselling services by the target groups, Strengthening the self-determination and self-control of the actors, Behavioural changes in dealing with extreme events* and *Behavioural changes in how counselling services are used* have reached means over 4 (see Appendix A - Table A4).

Table 5: Possible specific impact objectives of the impact sphere Behavioural Changes of Actors.

Behavioural Changes of Actors	• Activation and mobilisation of actors • Contribution to increasing social stability • Contribution to increasing economic stability • Development of counselling services by the target groups • Strengthening the self-determination and self-control of the actors	• improvement of knowledge transfer between actors • Behavioural changes in agriculture & horticulture • Behavioural changes in dealing with extreme events • Behavioural changes in how counselling services are used • Interconnection of actors

Source: own table

Information and Communication

65% of the respondents in 2019 and 78% of the respondents in 2020 assessed *Information and Communication* as an important impact sphere in their research projects. Six of seven possible impact goals (Table 6) reached mean grades over five (see Appendix A - Table A5). It becomes apparent that most projects want to enhance the communication process within institutions and between actors and organisations and enhance knowledge transfer.

Table 6: Possible specific impact objectives of the impact sphere Information and Communication.

Information and Communication	• Development of decision-making aids, solution approaches and recommendations for action • Software tools for information and communication • Improving communication within organisations (e.g. administration)	• Improving communication between organisations and external stakeholders • Improving communication between stakeholders • Improve dialogue between all actors in the project • Improving knowledge transfer within institutions (e.g. administration)

Source: own table

Green Infrastructure

In 2019, 71% of the participants rated green infrastructure as an essential sphere within their projects. In 2020, 68% of the respondents selected green infrastructure as one impact sphere of their projects. All potential impact goals (Table 7) are rated high by the respondents. Particularly the objectives *enhancement of climate resilience through green infrastructure* and *Awareness-raising regarding green infrastructure* are assessed as very important goals for the research projects. All objectives are rated higher in 2020 than in 2019 (see Appendix A - Table A6). Possibly this is affected by the lower respondent rate in 2020. Conceivably also, the process and status of the projects have influenced the ratings, as in 2020, the foci of the projects might be sharpened.

Table 7: Possible specific impact objectives of the impact sphere Green Infrastructure.

Green Infrastructure	• Increasing climate resilience through green infrastructure • Increasing the climate resilience of green infrastructure • Strengthening the initiative of the actors regarding the use & improvement of the green infrastructure	• Improvement of fresh air supply through green infrastructure • Improving awareness of green infrastructure among stakeholders • Improving water retention & stormwater management

Source: own table

4.1.3 Applied methods and achievement of impact objectives

The survey from 2019 shows that a wide range of methods is used in the projects (RQ/IL/b). It focused particularly on the living laboratory method (47 mentions) and other participatory methods (43 mentions) as well as interviews (46 mentions). Observations (39 mentions) and standardised surveys (35 mentions) are also indicated. Experiments played a subordinate role among the respondents (19 mentions).

As part of the 2020 survey, stakeholders were asked to rate the importance of the methods used to achieve the impact goals. Table 8 shows that all methods contributed to the achievement of the impact goals. Experiments, interviews, participatory methods and the living laboratory method were rated very positively. However, the contribution of standardised surveys to the achievement of objectives was perceived very differently by the actors who used this method. The average score is 5.11, but the standard deviation is 1.34.

Table 8: Contribution of the applied methods to achieving impact objectives. Assessed in 2020.

Applied Methods	N	Mean	SD	No contribution	Low contribution	Less contribution	Neutral	Contribution	High contri-bution	Very high contribution
Observations	22	5,55	1,06	0%	0%	0%	18%	32%	27%	23%
Experiments	19	6,16	0,76	0%	0%	0%	0%	21%	42%	37%
Interviews	35	6,06	1,00	0%	0%	0%	9%	20%	29%	43%
Participatory Methods	34	5,97	1,06	0%	0%	3%	6%	21%	32%	38%
Living Laboratory	43	5,86	1,15	0%	0%	0%	16%	23%	19%	42%
Standardised Surveys	27	5,11	1,34	0%	4%	7%	22%	22%	30%	15%

Source: own table

4.1.4 Interim summary intervention level

The descriptive statistics of the survey give insights into the case study, the characteristics of the research projects and their impact objectives. The empirical results demonstrate a comprehensive understanding of the concept of "climate resilience". The attributes defining the complexity, interconnectedness and system character of the term, *complex* and *multidimensional,* are ranked over 6. The respondents assess the attributes *long-term oriented* and *future-oriented* also with means above 6. Interestingly the attributes *transforming* and *proactive* got slightly lower ratings, even if these attributes are tightly bound to *future-* and *long-term oriented*. *Anticipatory, adapting* and *learning* are ranked as well higher 6. This rating underpins the evolving character of resilience in the respondents' perception. *Obtaining, regenerating,* and *reactive* are rated between four and five. These attributes are assigned to the characteristic of ecological resilience, focusing on the recovery and preservation of a system. Overall the respondents assess the concept of resilience as a highly complex and multidimensional, evolutionary and future-oriented concept.

In order to characterise the projects in more detail, the impact spheres are important (RQ/IL/a). According to the participants, *Capacity Building, Management and Planning, Information and Communication,* and *Green Infrastructure* are most important within the projects. *Guidelines and Principles*, *Monitoring and Precautionary Systems*, *Finance* and *Technology* are less represented within these projects. This result can be explained by the focus of the BMBF funding programme in which the case study took place.

RQ/IL/a focused further on the impact objectives of the projects. Firstly, as the projects have different specialised impact spheres, overarching impact objectives were assessed. The respondents reported ten of fifteen overarching impact objectives as "very important". On the one hand, this highlights the comprehensive scope of the projects. However, on the other hand, it underpins the interconnectedness of different objectives within climate change adaptation action. Furthermore, it becomes apparent that potential technological aspects of adaptation like *Improvement of energy-efficiency* or *Improvement of resource-efficiency* are not the focus of the projects. This finding is in line with the findings regarding the impact spheres.

Reviewing the survey results on the specific impact objectives, it became apparent that the empowerment of actors and supporting decision-making processes are main cross-cutting targets. The empowerment concept is assessed through the potential impact targets: *Activation and mobilisation of actors*, *Strengthening the self-determination and self-control of the actors, Strengthening the initiative of actors regarding the use and improvement of the green infrastructure*. The projects of the funding initiative mainly address empowerment targets through activities in Capacity Building, Behavioural Change of Actors and Green Infrastructure. Additionally to the narrow concept of empowerment, awareness-raising activities and knowledge transfer also influence the empowerment of actors. Awareness-raising activities are the main targets of projects in the spheres of green infrastructure and behavioural change. Knowledge transfer enhancing measures are conducted in the spheres of capacity building and behavioural change.

Developing and providing solutions for decision-making processes and recommendations for action are central targets in the spheres of Management and Planning, Communication and Information and Behavioural Change. The impact targets in the context of decision-making processes are essential, on the one hand, to enhance the empowerment of actors through knowledge, and on the other hand, are helping to steer the complex transformation process. Additionally, the high rated importance of communication enhancing measures (within an institution and between institution and stakeholders) reflects the difficulties of Germany's federal structure and the unresolved responsibilities and competencies of Departments at all governmental levels, as climate change impacts are cross-cutting challenges.

Further, the empirical results give insights into the broad focus and integrating character of the projects included in the case study. Many potential goals are rated high, and only very few are rated as irrelevant (under 0) within the projects. However, this conspicuousness indicates that one adaptation action impacts different impact goals. Which also shows the complexity of reciprocal effects in multidimensional and interrelated systems.

The projects aim to reach the impact targets with a versatile mix of methods (RQ/IL/b). The living laboratory method, a highly participative method, is implemented in most projects. Overall, the projects focus on qualitative methods for measurement implementation. Regarding Table 8 it becomes apparent that interviews and the living laboratory method are assessed as highly contributional to achieving the impact goals, followed by experiments and other participative methods. Standardised surveys are assessed as less contributional. These results underline the need for and importance of stakeholder involvement for the impact objectives achievement.

Overall, it is essential to note that no minimal or maximal number of respondents for each project was set for the survey. Consequently, two respondents may represent one project, whereas seven respondents might represent another project. Nevertheless, the empirical results give a broad understanding of the case study and the focal points of the adaptation measures.

4.2 System level: Monitoring on the urban and regional scale

An intervention aims to have an impact on the social-ecological system. However, how can the system level be assessed? The peer-reviewed and published articles, which aim to answer these questions, are briefly summarised and presented in the following two chapters.

4.2.1 Measuring the urban scale – First contribution

The first article, "*Indicators for Monitoring Urban Climate Change Resilience and Adaptation*"(see Appendix B), published in 2019 in the journal *Sustainability*, focuses on how climate resilience can be assessed on the urban scale (RQ/SL/a). The article analyses the importance and challenges of monitoring and evaluation in the context of urban climate resilience and aims to develop indicators for monitoring and evaluation on the city level. Central to the development of the indicator set are the conditions of

- context specificity of industrial nations, especially Germany
- easy data availability, if possible, as secondary data
- manageable and user-friendly number of indicators to enable its application in the municipalities and projects

To meet these goals, the 14 projects from the BMBF's funding initiative "Climate resilience through action in cities and regions", where researchers, consultants and practitioners are integrated, were involved in developing the resilience framework and the indicator development.

The research followed a multistage process (Figure 10). Within Phase 1-3, a definition of urban climate resilience was devised, and the MONARES resilience framework was developed (see Chapter 2.4.4). The MONARES framework consists of five dimensions (environment, infrastructure, economy, society and governance), which are divided into 24 action fields (see Appendix B-Table 1).

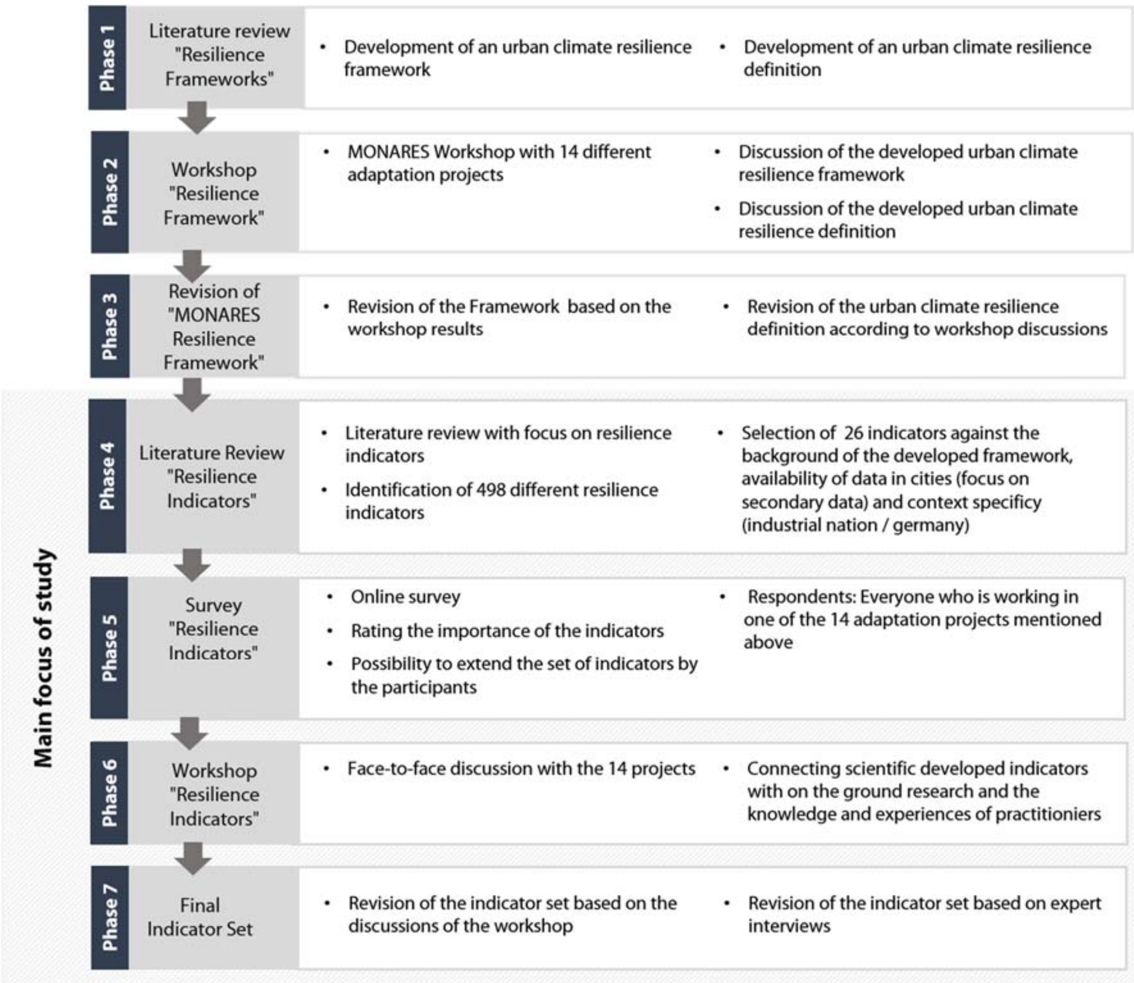


Figure 10: Research process of the study.
Source: slightly adapted, Feldmeyer et al. 2019

Based on these preliminary steps and results, the actions fields were operationalised by indicators. The generation of the indicators set was conducted through a four-step mixed-method approach (phases 4-7). First, based on a literature review that identified 498 different resilience indicators, 26 indicators were selected in light of the MONARES framework and data availability in cities. Second, the selected indicators were given to the experts from the projects to assess their relevance for climate resilience (Phase 5). At this stage, there was also the possibility to suggest additional indicators. Third, after a first survey evaluation, the results and each indicator were discussed in an expert workshop. The indicator set was then revised and finalised. The final indicator set consists of 23 indicators (see Table 9), which operationalise the dimensions and actions fields of the MONARES framework. For a detailed discussion of each indicator, see the publication (Appendix B).

Table 9: Final MONARES indicator set.

Dimension	Action field	Indicator
Environment	Soil and green spaces	Degree of unsealed ground
	Water bodies	State of the 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 treatment	Number of springs
		Adapted sewer system
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
	Health care	Number of doctors
	Sociodemographic structure	Share of citizens ABV 6 / U65
	Civil society	Associations per 10.000 capita
	Civil protection	Fire brigade volunteers
Governance	Participation	Number of participation processes
	Municipal budget	Debt per citizen
	Strategy, plans and environment	Risk and vulnerability analysis
		Strategies against heavy rain and heat in plans
	Administration	Inter-offices working groups regarding risk, climate change and resilience

Source: slightly adapted, Feldmeyer et al. 2019

Furthermore, the paper discusses the conflicting goals between a user-friendly and a comprehensive indicator set. Within the survey and especially during the workshops, researchers tended to prefer larger indicator sets to get a comprehensive and detailed indicator set. Otherwise, practitioners endorsed compact indicator sets by focusing on manageability in practice. Therefore, the

MONARES Indicator set aimed to compromise comprehensiveness and practicability. Besides these aspects, it is pointed out that within municipalities, limiting factors for monitoring are deficiencies in data provision, data handling, data collection and financing.

Nevertheless, it is essential to mention the possibility of trade-off effects and conflicting goals between indicators, forcing competition for scarce resources (e.g. ground, money and water). Reciprocal effects between indicators can arise, which is critical to finding adequate solutions for improving cities' climate resilience. Therefore, the developed indicator set pronounces the contribution of each action field to resilience-building by waiving on an overall resilience index.

The applied mixed-method approach proved to be highly beneficial for indicator development. Using this approach, an inter- and transdisciplinary process leads to an indicator set that compromises science and practice goals. Further, the transparency of the process and the indicator set can enable the set's application and enhance monitoring and evaluation at the city level in Germany.

4.2.2 Measuring the regional scale – Second contribution

The second contribution, "*Regional climate resilience index: A novel multimethod comparative approach for indicator development, empirical validation and implementation"* (see Appendix C), was published 2020 in the journal *Ecological Indicators*. This paper deals with the question of how climate resilience can be assessed on the regional scale (RQ/SL/b).

While the first article focuses on the urban scale and is not developed as a composite index, article two aims to build a regional composite index. Firstly, the article discusses the benefits and challenges of composite indicators (CI), which are very beneficial for multidimensional phenomena in order to grasp all facets. Furthermore, CI can enhance the understanding, monitoring and evaluation of complex circumstances and support agents' behavioural change. However, criticisms of CI are made of a) the possibility of misleading and non-robust results; b) missing objectivity due to the often-subjective indicator selection process; and c) difficulties regarding the application of the indicators due to high complexity and the high amount of needed data (Saltelli 2007). Nevertheless, the benefits of CI are significant in the context of climate resilience and natural hazards, as these are highly complex and context-specific phenomena.

The authors present an approach to 1) upscale the urban climate resilience to a regional climate resilience; 2) address the mentioned criticisms of CI by testing different aggregation methods; 3) empirical validation, and 4) develop an indicator set for regional climate resilience. This research is further designed as a case study on the regional level and uses the federal state of Baden-Württemberg as a study area.

The authors use the MONARES indicator set (MIS), presented in article one (Feldmeyer et al. 2019), as the basis for the upscaling process. First, the dimensions of the MIS – environment, infrastructure, economy, society and governance – were adapted to the new framework. In the next step, the action fields of the MIS were adjusted to the regional level by considering the planning duties – mandatory and voluntary – of the administrative district level. These considerations resulted in a set of 17 action fields/themes, which were operationalised by 23 indicators (see Appendix C – Table 2).

As the indicators do not have the same scales, they were normalised by min-max transformation within the subsequent step and validated by using a machine-learning approach afterwards. Based on these results, the indicators were aggregated by four different approaches (equal weights, mixed equal hierarchical expert weights, Wroclaw Taxonomic Method, Mazziotta-Pareto-Index) to find the most appropriate aggregation method. Further, the reliability of the indices was tested by Cronbach's Alpha and Guttman's Lambda, and the sensitivity of the indices was calculated by using global sensitivity analysis (GSA) by applying the Bayesian approach. In the ensuing step, the aggregated indices were empirically validated (non-linear and non-parametric correlation). Finally, the validated indicators and the most adequate aggregation method was selected and applied to Baden-Württemberg.

The GSA and the correlation analysis demonstrate that the index aggregated by Wroclaw Taxonomic Method performs best. The final Regional Climate Resilience Index (RCRI) consists of 17 indicators (see Table 10). The developed index was applied to Baden-Württemberg. In order to get more insight into each indicator, the dataset was partitioned into the ten most resilient and ten least resilient administrative districts and metropolitan and rural areas. Finally, the authors presented the overall RCRI on a map.

The comparison between metropolitan and rural administrative districts reveals that, based on the index, metropolitan areas have a (statistically) significantly higher overall climate resilience than rural areas. Metropolitan areas have higher values for the indicators *GDP*, *Accessibility of supply with daily goods*, *Proximity of hospitals*, *Nearby doctors* and *Nearby police stations*. The indicators reflect the benefits of infrastructure in urban areas. Nevertheless, rural areas get better rates regarding employment and environmental indicators. It is important to mention that the high employment rate in the rural regions is very special to the sample of Baden-Württemberg.

Hidden champions have production sites, innovations centres and headquarters in many of these regions.

Overall, the authors point out that the metropolitan areas need to enhance their environmental resilience and social resilience, whereas the rural areas need to enhance their infrastructure. Nevertheless, it is critical to enhance and integrate all parts of resilience in a balanced way. The study demonstrates the importance of empirical validation and the possibilities for machine learning within indicator development.

Table 10: Regional climate resilience indicators. Green shaded indicators are final selected indicators.

Sphere	Theme	Indicator	Indicator Code
Environment	Soil and green spaces	Degree of ground sealing	en_pe
	Water bodies	Proportion of structurally shaped settlement and traffic area in the official flood area	en_wa
	Biodiversity	Share of nature conservation and protection areas	en_bi
	Air	Air emission index	en_ap
	Agriculture and forest	Degree of organic farming	en_ag
		Proportion of undissected forests	en_fo
Infrastructure	Streets	Accessibility of large centres	in_sp
	Health care	Hospital beds	in_ho
		Nearby doctors	in_dp
	Local supply	Accessibility of supply with daily goods	in_lp
	Public transport	Proximity of public transport	in_pu
Economy	Innovation	Employees in research-intensive companies	ec_re
	Employment	Employment	ec_em
	Economy	Gross Domestic Product	ec_gr
Society	Health	Sick days	so_he
	Sociodemographic structure	Share of citizens ABV6/U65	so_ag
	Civil society	Voter turnout	so_vo
	Social security	People in need communities	so_sp
	Civil protection	Nearby police stations	so_pp
	Civil protection	Proximity of hospitals	so_ap
Governance	Budget	Municipal debts	go_dp
		Municipal income	go_in
	Administration	Support of climate protection agreement	go_su

Source: slightly adapted, Feldmeyer et al. 2020

The importance of considering all five spheres (Environment, Infrastructure, Economy, Society and Governance) is pronounced and empirically validated within the research, which emphasises the social-ecological character of climate resilience. Further, the equal importance of indicator selection and selection of the aggregation method is also stressed within this research. Regarding indicator selection, difficulties exist concerning data availability at the administrative district level, e.g. status of water bodies and forests or members in the voluntary fire brigade. The authors, therefore, call for better availability of data in the sense of open data within government and administrations. Moreover, the authors stress that the number of indicators within this study was relatively limited, and the empirical analysis of more indicators can provide a better understanding and assessment of climate resilience. Besides quantitative and secondary data, the authors highlight the importance of qualitative and primary indicators to assess contextual factors, like social networks, feeling of belonging, trust in authorities, knowledge and risk perception, which play a pivotal role in climate resilience.

4.3 Actors' level – Assessing knowledge and action changes – Third contribution

The third publication, "*Measuring knowledge and action changes in the light of urban climate resilience"* (see Appendix D) was published in 2021 in the journal *City and Environment Interactions*. This paper focuses on measuring the effects of adaptation measures on the actors' level (RQ/AL/a).

Firstly, the authors analyse the need to monitor the short-term impacts of adaptation measurements and the measurement on the actors' level. On the one hand, most indicator sets, as well as publications one and two, focus on quantifiable ecological, economic and socio-economic data (Bakkensen et al. 2017; Cutter et al. 2010; Cote, Nightingale 2012; Tyler, Moench 2012; UNDP 2020; Wardekker et al. 2020) on the system level. On the other hand, the transformation towards a resilient urban system can only be performed by actors (Williams et al. 2015) by changing their specific behaviour, identity, norms and values (O'Brien 2016; Otsuki et al. 2018). Therefore, the individual sense of responsibility and individual activity is essential for the transformation. Consequently, it is crucial to understand the individual agency regarding climate resilience (Brown, Westaway 2011; Folke et al. 2005; Masterson 2019; Westley et al. 2013).

The authors developed a framework to measure the citizens' individual climate resilience agency and especially of actors within an adaptation intervention. Then, as repeated measurements are essential for monitoring, they aimed to develop a tool that can be used for both one-time assessment and repetitive measurement.

Resilience is very context-specific and a broad concept. Consequently, there are no specific, quantifiable knowledge items that can be assessed. Therefore, the authors measured preconditions that might enhance the Individual Climate Resilience Agency (ICRA) (see Figure 11).

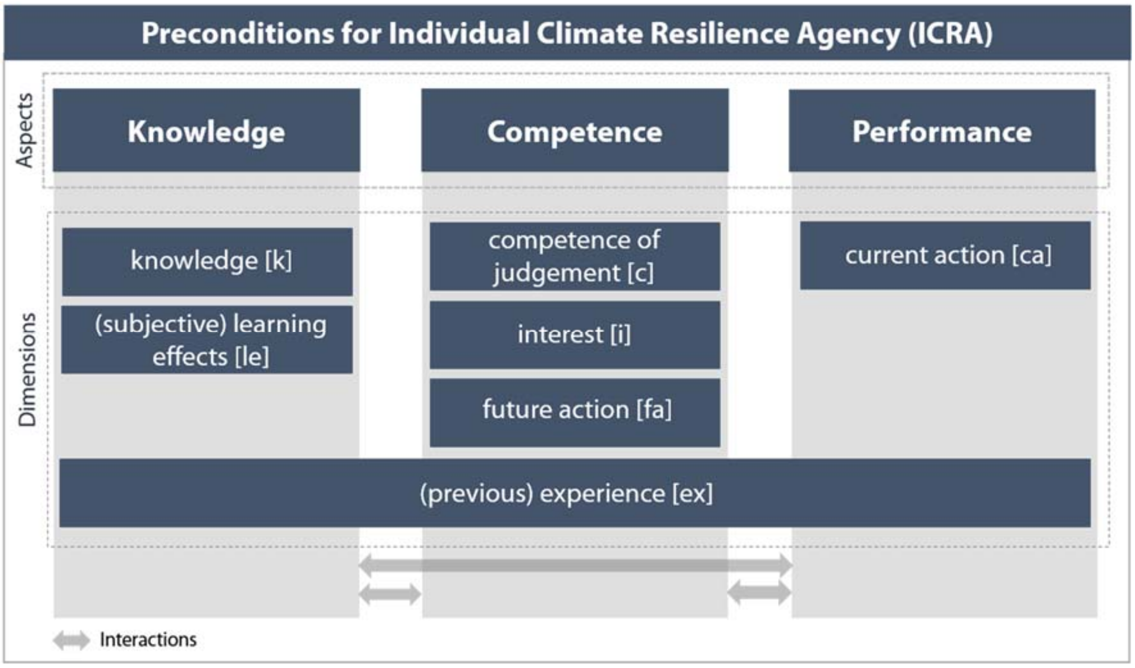


Figure 11: Deconstructed preconditions for Individual Climate Resilience Agency (ICRA)
Source: Wilden, Feldmeyer 2021:4

The 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 (Kurtz 2010) and consist therefore on the three aspects: knowledge, competence and performance. First, these aspects were deduced into seven dimensions – knowledge, subjective learning effects, competence of judgement, interest, future action, current action and (previous) experience. In the next step, these dimensions were operationalised through individual indicators. Finally, the developed 21 indicators were combined on a theoretical basis to five composite indicators – basic knowledge, experience and current action, learning effects, ongoing (behaviour) changes and future engagement. In the next step, these indicators were implemented in an exploratory standardised online survey to test the survey tool and gain data for the empirical validation of the indicators and the structure of the composite indicators. The survey was conducted in 2019 (n=59) and 2020 (n=53) within the 14 cooperation research projects.

The test of reliability with c-alpha revealed a very good consistency of the theory-driven composite indicators. While validating the theory-driven composite indicators with the Principal Component Analysis (PCA), it became apparent that most individual indicators are structured in the same way by empirical data, yet a different composition is also conceivable in some cases. Nonetheless, the authors suggest the theory-driven composite indicators as they have many benefits for practitioners, e.g. five indicators give a more detailed picture than four, and most importantly, the composition is the same through every measurement.

The analysis of the ICRA using the empirical data revealed that transferring knowledge and awareness into behavioural changes is possible, even in a one-year timeframe. Previous experience seems to have less influence on actions changes and knowledge than anticipated initially. However, this might be a finding of this specific sample (staff of research projects in the context of climate adaptation and resilience), as all respondents already deal with climate resilience for a longer time and their professional context. Therefore, this finding needs to be explored in detail in future research.

Overall, the authors suggest integrating actor-based indicators into the set of system-based indicators. In connection with the MONARES indicator set, an assignment of the ICRA approach within the dimension of society and action field "knowledge and risk competence" is suggested. In addition, it also noted that gathering primary data increases effort and is both time consuming and resource-dependent compared to secondary data. Nevertheless, the application of the ICRA or other individual climate resilience indicators is highly recommended as they are not included in existing data sources and are needed to monitor resilience building. Furthermore, using the ICRA approach supports monitoring and evaluation at individual level and a short/medium-term timescale, which is an indispensable benefit in an accelerated world.

Furthermore, the measurement of the preconditions of climate agency also provides insights into potential long-term effects. A further benefit of the developed tool is the possibility of self-evaluation with the tool. This opportunity also accelerates the measurements' processes and can enhance and accelerate the learning process. The authors conclude that the research shows that actor-based measurements can monitor short-term changes and evaluate specific adaptation measurements. Further, the developed approach can be scaled up and can also be used in rural regions. Also, the adjustment to specific aspects of resilience is possible.

4.4 Integrating the three levels into one monitoring and evaluation approach

As emphasised in Chapter 2.7, an integrated approach is needed to deal with the challenges climate change, climate adaptation and climate resilience pose to societies, policymakers, decision-makers and change agents. Further, increasing the integration of actor and action-focused monitoring approaches is also of significant importance (Grothmann, Michel 2021). Therefore, the three levels (intervention, system, actor) should be treated together for enhancing the possibilities of comprehensive monitoring and evaluation, learning effects and decision-making processes and finally, navigation of climate-resilient pathways.

In order to steer the social-ecological transformation, the combination of the approaches is essential. The assembling of the assessment levels has numerous benefits, including

- potentially negative interactions and maladaptation can be recognized very early,
- diverging impacts on different scales can be identified,
- better assessment of the interconnected and multiscalar system,
- enhancement of learning effects,
- improvement of participative activities,

to make well-informed decisions and track progress.

Hereafter, the possibilities of an integrated approach for monitoring and evaluation of an adaptation measure are presented. The evaluation can be both summative and formative. Referring to the logical model (see Chapter 2.6), the developed indicator sets of the regional scale, the urban scale, and the actor scale provide information about the initial/target system in which the interventions occur (Figure 12). The *initial/target system* is the social-ecological system, or more specifically, in this case, the urban social-ecological system. In order to measure the initial system, a baseline measurement should be applied with the Regional Climate Resilience Index, the Urban Resilience Indicator Set (MIS), and the actor-focused indicator set (ICRA).

The assessment of, e.g. the impact objectives and applied methods within an adaptation measure is conducted on the intervention level. Thus, *input*, *concept, process/activitie*s and *output* are appraised on the intervention level. The *outcome* of an intervention/measurement is defined as the effects on actors or the target groups. Here the actor-focused indicators can be applied to measure these effects. The *impact* of an intervention/measurement is defined by the effects on the system level, which is the urban and regional system in this research. Therefore, the regional and urban resilience indicator set can be applied to assess the long-term impacts.

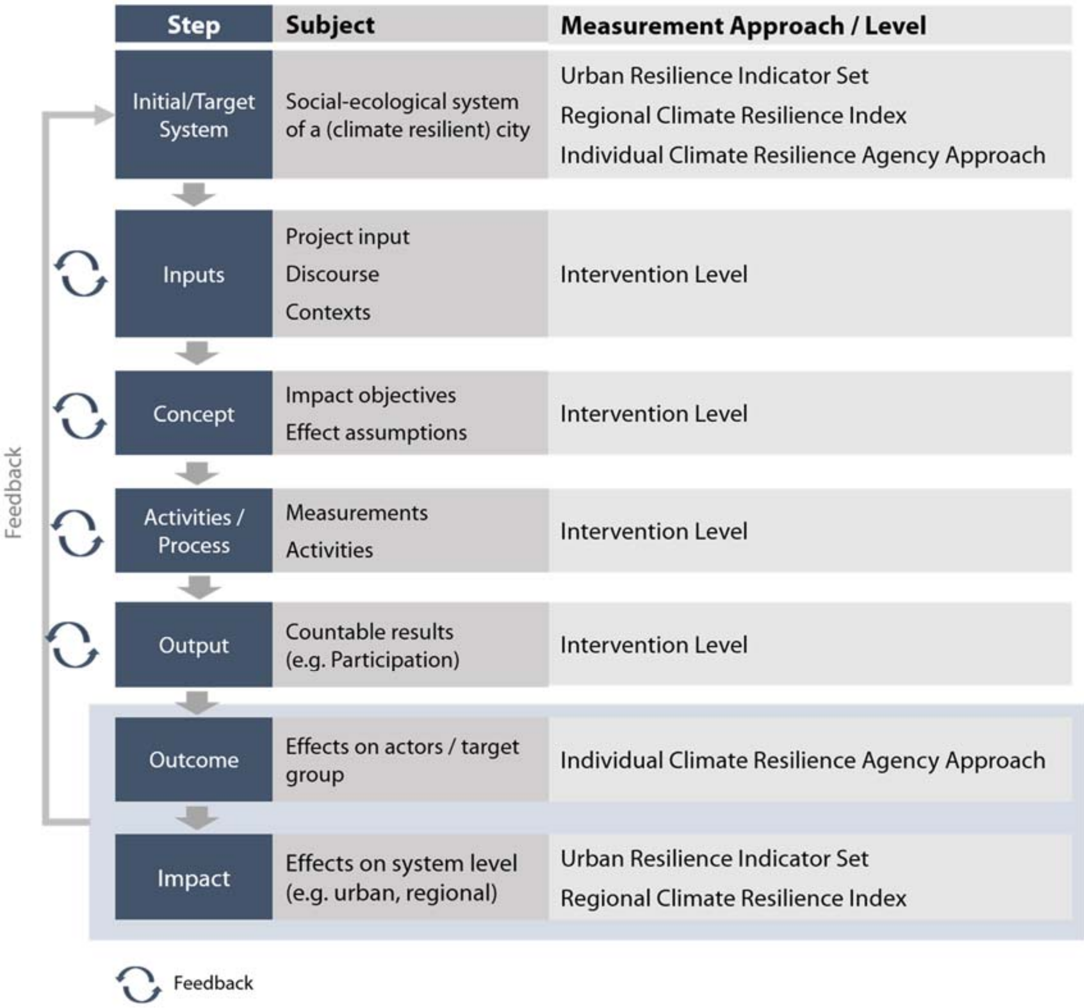


Figure 12: Model for climate change adaptation interventions. Complemented by suggested measurement approaches and levels.
Source: own figure

As within this approach, the social-ecological dimension is pronounced, the integrative view of both *outcome* and *impact* is important for monitoring and evaluating social-ecological systems. The monitoring and evaluation results of each stage, and thus each level, should be integrated into the overall feedback process that relates to and influences the baseline/target system.

Hereafter, each assessment scale's benefits, limitations, and implementation possibilities are discussed more in detail. The **Regional Climate Resilience Index** should be implemented as regular resilience monitoring on the regional scale. Due to the scale, the indicators are relatively slow in responding to changes on the local scale (e.g. impacts of one adaptation measure). For example, enhancing urban green might not directly be illustrated by the regional indicators due to scale effects. Nevertheless, the indicators can assess the cumulative effects of multiple adaptation measures or other interventions implemented in the region.

The **Urban Climate Resilience Indicators / MIS** are also relatively slow responding to measures but (partly) faster than regional indicators. These indicators assess the urban system and enable more profound insights into the specific urban system. For example, measures on the neighbourhood scale might be visible within a short time frame, whereas the indicators do not illustrate measures on the street scale (e.g. planting ten trees). However, the whole urban system is assessed through these indicators. Therefore, it enhances the possibility to register relatively early changes in urban system's resilience. As the urban indicators are important for more than one intervention, they should be regularly assessed by the citiy's government.

The **indicators on the actors' level** are assessing knowledge and behaviour (changes) of the residents or participants. The actor-based approach is vital to enhance the role of human agency and action within the mostly secondary data-driven, environmental and socio-economic data integrating monitoring systems and thus enabling more extensive social-ecological system considerations. In most interventions, e.g. a citywide PR-campaign for climate adaptation or a neighbourhood urban green action, latent but central goals are enhancing knowledge regarding the specific topic and behavioural changes within daily life. These changes can occur already within a brief period of time. The indicators can be assessed both citywide or within an adaptation activity, and can contribute to measuring the intervention effectiveness regarding knowledge and behavioural changes.

Moreover, this level is an essential element for evaluating the implemented participative methods and enhances the overall knowledge regarding the effectiveness of these measurements. Thus, monitoring the actors' level can enhance the formative evaluation and, consequently, the intervention's steering. Additionally, citizens' overall knowledge and behaviour regarding specific parts of climate resilience could be assessed by implementing the indicators within citywide regular surveys. In order to integrate the actor-based measures into the Urban Resilience Indicator Set, the indicators enhance the *Social* Dimension, especially action field *Knowledge and Risk Competence*. Additionally, the indicators also support the *Governance* Dimension by getting more profound insights into the action field *Participation* as statements can be made about the effectiveness of the participation processes.

The data gathering on the **intervention level** focuses on assessing the impact spheres, impact objectives, applied methods and achievement of the targets. The assessment of these elements should take place within an adaptation measure. In order to reduce the workload at the intervention level and enhance the steering potential within the adaptation measurements, the urban and regional scale indicators should be provisioned by higher administrative levels. By providing and applying the monitoring data of the urban and regional scale, the actors within the intervention can incorporate them and consider the data of the intervention levels with the higher levels. Consequently, the implementing actors can be empowered within their governing processes.

Beyond implementing a monitoring and evaluation approach within adaptation measures, the developed and validated indicator sets on the regional, urban and individual scale can be applied to a baseline assessment and regular monitoring.

5 Shaping climate resilient pathways!

"We have never had to deal with problems of the scale
facing today's globally interconnected society.
No one knows for sure what will work, so it is important
to build a system that can evolve and adapt rapidly."
Elinor Ostrom

In order to navigate and, especially, to be able to develop effective and meaningful measures and strategies within this highly complex, adaptive urban and social-ecological system, evaluation and monitoring are essential to reduce complexity and empower actors at all scales. The presented work assesses climate resilience and the effects of climate adaptation measures on different scales, which are all relevant for assessing the interrelated effects of these measures.

5.1 Research Objectives: summary

The presented research contributes to the discourse of monitoring and evaluation of resilience and climate change adaptation. Different measurement tools are developed within this research on three different levels (regional, urban and actor). As climate resilience and climate change adaptation are highly complex, multidimensional, multiscalar, and context-specific, integrating all three levels into one monitoring and evaluation process is essential (see Chapter 4.4). The developed approach introduces a concept that combines system-based monitoring approaches with an actor-based approach. This concept can provide insights into the multiscalar and intertwined ties of climate resilience and the impacts of adaptation measures. The detailed research questions on the levels are summarised first in the following sections. Subsequently, the main research question is addressed and finally concluded.

Intervention level (IL): How can interventions on the local level be characterised? (RQ/IL)

Characterising and analysing the interventions by impact spheres, impact objectives (overarching and specific) and applied methods are essential to assess the desired impact system. Inputs like resources (personal, financial) were not included in this research. The monitoring of the impact objectives (overarching and specific), the methods applied, and the personal perception of the actors working in the cooperating projects regarding the contribution of the method to achieve the impact objectives are carried out in an exemplary and descriptive manner. The interventions analysed mostly focus on the impact of capacity building, management and planning, behavioural change, information and communication, and green infrastructure. It is crucial to mention that each project incorporates more than one sphere as well as many different impact objectives. On the one hand, this finding emphasises complexity and multiscalarity of the interventions and the systems addressed, and on the other hand, the necessity of sharpening the target in the adaptation projects.

The foci of the interventions also reflect the identified areas for action. Besides empowerment and knowledge transfer, the urgencies for integrated (urban) planning and guiding principles, as well as better communication processes between and within institutions, are revealed. These focal points also emphasise the urban system's capacity enhancement and the essential importance of integrative governance. Further, the central role of local actors and stakeholders is highlighted by the stated importance of participative methods within the adaptation design, supporting the essentiality of actor-focused measurements in monitoring and evaluation.

System level (SL): How can climate resilience and the impacts of climate adaptation interventions be assessed on the system level (e.g. urban system, regional system) (RQ/SL)

The research question is answered by two approaches on two different scales – urban and regional – to assess resilience on different temporal and spatial scales. An indicator set is developed and validated to assess climate resilience on the urban scale. The indicators are based on secondary data, mostly available within the municipalities. An indicator set is also developed and empirically validated on the regional scale. In contrast to the urban resilience indicator set, the regional resilience measurement is designed as a composite index, the RCRI. It consists of 17 indicators which are also based on secondary data mostly. The scale-specific indicator sets reflect the importance and possibilities of spatial scales in monitoring context as on different spatial scales, different (temporal) impacts and changes can be assessed. Therefore, a comprehensive system-level status can be gathered by reflecting both scales. Nevertheless, the indicator sets on system-level are missing community and individual-focused indicators regarding social, climate-justice and cultural dimensions of climate resilience.

Actors' level (AL): How can an assessment on the actor level contribute to monitoring and evaluating adaptation measures and the navigation of climate-resilient pathways. (RQ/AL)

The presented research reflects the essential role and possibilities of the actors' level in the context of monitoring and evaluation of adaptation measures. The transformation process to climate-resilient societies and spatial systems is constructed and performed by the actors by changing their behaviour, identity, norms and values (Wilden, Feldmeyer 2021).

Besides the public discourse, adaptation measures also influence these individual aspects. Therefore, a tool to measure individual knowledge and behavioural changes regarding climate resilience was developed to include the individual level in monitoring and evaluation within the research and combine the system-focused indicator set with actor-focused measures. Changes on the actors' scale are an overarching objective of many adaptation measurements and reflect the direct impacts on individuals induced, e.g. by an adaptation intervention. The developed survey tool and indicators measure the preconditions for an individual climate resilience agency and the indicators are also validated empirically. Research suggests that these changes can be captured quickly by using a validated survey and indicators. Therefore, evaluation at the actor level plays a crucial role in monitoring and evaluating adaptation interventions, as formative evaluation can occur during the process based on the evaluation process results. Further, as pathways are shaped by action and behaviour, it is essential to integrate human behaviour into complex adaptive systems (Grothmann, Michel 2021).

How can climate resilience and the impacts of climate adaptation measures be monitored and evaluated? (MQ/a)

Climate resilience and the impacts of adaptation measures are reflected at different levels, timescales, and in different manners due to the decoupling effects of the cause-effect chain. Therefore, it is essential to scale down to the relevant and manageable levels to reduce the complexity of the monitoring and evaluation process. Accordingly, the presented research deals with three levels of analysis (intervention, system and actor), two spatial scales (urban and regional), and includes three temporal scales (short, medium and long-term). The intervention level is the basis for the impact assessment as on this level, the impact objectives and methods used are assessed. The system level is divided into the urban scale, which includes mid- and long-term assessment, and the regional scale, which includes mid- but focuses on long-term impacts. Finally, on the actors' level, short-term changes of individuals can be assessed. Therefore, for the monitoring and evaluation process, indicators are needed. Furthermore, as the levels focus on various parts of the overall system, specific indicators are required for each level. These are developed and validated in the presented research.

How can the complexity of social-ecological systems be transferred into an applicable and integrative monitoring and evaluation approach? (MQ/b)

Due to the complexity of social-ecological systems, integrated and applicable measurement of these systems is challenging. However, it is of particular importance that the measurement of these systems is also possible by the actors and institutions that design interventions and guide the process of building climate resilience and adaptation through frameworks, policies and interventions. The social-ecological system of urban climate resilience was deduced in the previous chapters and divided into specific levels (intervention, system, actor). Indicators and measurement options were presented for each of these areas. Each of these areas can be measured and evaluated on its own. However, an integrated and comprehensive picture of the social-ecological system can only be obtained by integrating and re-abstracting the individual levels and building blocks. On the one hand, this procedure reduced the complexity of the system to be examined against the background of climate resilience, but on the other hand, based on an integration of the validated levels, it made it possible to consider the system as a whole.

How can leading actors (e.g. local governments) identify if their actions (e.g. interventions, decisions) contribute to the goals of climate adaptation and the enhancement of climate resilience? (MQ)

Leading actors in climate change adaptation are confronted with a highly complex adaptive system. Hence, they are confronted with reciprocal and multiscale effects due to climate and social change acceleration, with a reduced left timeframe for climate action and decision-making. Repetitive monitoring and evaluation enhance their possibilities of shaping a climate-resilient future and well-informed decision-making processes.

Reflecting on the previous paragraphs, it is apparent that the impacts of climate resilience and climate adaptation measures can be monitored and evaluated on different levels and by different methods. Firstly, leading actors must define the objectives of an intervention they want to achieve – measurement takes place on the intervention level. Secondly, the initial system on both the system level (urban and regional scale) and the actors' level needs to be assessed to get a baseline for further measurement. By assessing the different levels regularly, short-, mid-, and long-term changes can be identified. Using the presented approach as a formative evaluation tool will accelerate the context-specific adaptation and monitoring process.

To achieve the opportunities of the suggested monitoring approach, some main challenges to enhance on the one hand the possibilities of research as well as the application of monitoring and evaluation approaches need to be tackled by politics and governments on each scale – data availability and communication between departments. Thus, authorities need to enhance interactions across levels. For example, the monitoring of the regional resilience indicators could be established on the federal state level. On the city or municipality level, urban resilience indicators should be monitored. These levels could monitor the changes on the overall system changes. In reflection with this data, the monitoring and evaluation of the adaptation measure can take place on the level of an intervention. Such a process would enhance the guidance within climate-resilient trajectories essentially.

5.2 Critical reflections of the research

Different aspects limit the presented research. Most of these aspects are already pointed out within the articles. In the succeeding paragraph, additional limitations of the overall research are presented. Firstly, the indicators and indicator sets were developed and validated with data of projects within the funding programme "Zukunftsstadt" (Chapter 4.2.1, Chapter 4.3) and based on data of the federal state Baden-Württemberg (Chapter 4.2.2). Nevertheless, none of these indicator sets was applied to other case studies. Further, the integrative approach discussed in Chapter 4.4 is not yet tested in on the ground research.

Secondly, as MONARES was an accompanying research project, it had some restrictions that influenced and limited the methodology of the presented research. Due to the funding conditions, the projects had different starting dates of their funding period, and these diverging funding periods led to difficulties in implementing the evaluation process within the research projects. In addition, due to data protection law did not permit the implementation of actor-focused indicators as on the ground research within the cooperating projects.

Thirdly, the assessment approach and especially the number of indicators on each scale (regional, urban, actors) are developed within the dichotomy of scientific accuracy and manageability in practice. On the one hand, the scientific discourse aims to comprehend this impacts and effects to develop a broad understanding of the systems. On the other hand, practitioners in administrative districts, cities or especially rural regions are mostly lacking different resources – e.g. human, financial, time – to apply very complex indicator-systems and analysis. Nevertheless, practitioners at the forefront of adaptation to climate change are steering along further development pathways, with every decision they make. Therefore, they need easily applicable indicators helping in decision-making and resilience-building processes. The developed approach tries to balance these challenges and different needs. Consequently, the number of indicators in the indicator sets was reduced and, at the same time, each indicator is empirically validated to allow the best possible explanatory coverage with a small number of indicators and to exclude redundancy. Nevertheless, this conflict is both an aspiration and a limitation in this study. Further research is needed to reduce the trade-off between the number of indicators and a detailed description of a social-ecological system.

Fourthly, the question regarding data availability and responsibility is bound to the applicability of the indicator sets in practice. As contributions one and two specify, accessing the data required for some indicators was difficult. For example, an essential indicator for the abilities in the context of responding to extreme events could be the human resources of the voluntary fire brigade. The fire brigade is a cornerstone of civil protection, but data on human resources is not available on regional levels. Therefore, important and suitable indicators might be excluded due to reduced data availability on the different levels.

5.3 Future research and outlook

The limitations of the research lead to implications for future research. One central aspect in future research should be empirical testing and further validation of the indicators, especially the integrated monitoring approach in field research. Additional implementation and testing of the approaches are highly recommended to assess the possibilities, boundaries and potential for improvement. The subsequent questions should be addressed in future research:

- How do the indicators and indicator sets deal with the difficulties of place, context, and time-specificity?
- How does the integrative approach work over time?
- Do the indicators measure what they should measure?
- How do practitioners deal with the different indicator sets?

Additionally, the application of indicators aims to measure a social-ecological, urban system. The presented indicators are based on the current understanding of this specific system. Therefore, it is crucial to enhance the understanding of the cause and effect chains and reciprocal effects within the social-ecological urban system and its subsystems. Research approaches like system dynamics analysis, and complex adaptive system theory could shed more light on these intertwined systems.

Furthermore, the transformability of the indicator sets should be tested, both within Germany and in other countries, to gain more knowledge about specific needs and comparison possibilities. Therefore, e.g. the urban resilience indicator set should be applied in a rural region to generate knowledge regarding differences in application in urban and rural regions. Transferability is of high importance, especially as rural regions, e.g. in Germany, are not yet focused on climate change adaptation and often lack financial and personal resources. Hence, supporting by monitoring of climate resilience would be highly beneficial.

Besides transferring the urban resilience indicator set to other spatial categories, further research is needed regarding the individual level and agency. To drive the transformation to a climate resilient society, the individual agency of each citizen is needed for success. Therefore, more research is vital to gain knowledge, e.g. the interactions between individual agency and place identity, as well as the relevance of further socio-cultural indicators, as influential factors for climate resilience and climate action. In this context, central elements of the SDGs like social and environmental justice and health should be integrated into research and monitoring.

The presented research provides a starting point for assessing and evaluating the participation methods used and achieving impact objectives. Many different participation methods are implemented in adaptation measures. Understanding which method is most appropriate under which conditions and for which objectives is crucial for enhancing and accelerating the transformation to a climate resilient city and society. Therefore, further research is needed regarding the chain of effects between applied methods and impact achievement and suitable participation processes.

Beyond research concerning indicators, governance structures and guiding principles in climate change adaptation should be explored through the lens of Political Ecology, as power structures should be revealed more in detail. Identifying these structures could support developing action fields for enhancing building climate resilience. This leads further to questions concerning the relationships between climate resilience, health as well as social and environmental justice, which should be taken into account in future research.

The need for a transformation to climate-resilient societies opens up new possibilities for innovation and hold capabilities for redefining global relationships. A mutual learning process on equal footing between the Global North and the Global South would be more than desirable and necessary to accelerate learning processes and interchange adaptation methods in both directions.

5.4 Coming into action while listening to the world

"We still have a chance
to bring about a safe future."
Johan Rockström, 2021

Climate change, climate change impacts, climate resilience, climate adaptation, sustainable development, acceleration of social change, social-ecological transformation – these words and terms meanwhile characterise daily discourse. In the foreground, they are perceived as *en vogue* buzzwords. Yet, when closely examined, these terms draw a picture of highly complex, multidimensional, multiscalar and interrelated systems, in which many linkages are not yet visible and are bound by latent connections.

However, uncertainty and complexity must not lead to inaction. Many local actors are already assuming responsibility for shifting and shaping the specific pathways of their local communities and, thus, the overall pathways of society. Nonetheless, higher administrative levels are particularly responsible and in charge to act. They need to address climate resilience challenges and enhance, e.g. better integration of climate resilience and adaptation into planning by implementing a "resilience" or "adaptation check". Local authorities need more applicable guidelines and tools for dealing with climate change. The application of scale and system-integrating monitoring and evaluation might be an essential step for governing the pathways within a safe-operating space and supporting actors on all scales. The place and context-specific character of resilience needs to be reflected for each action and must be classified within the overall frame of the global social-ecological transformation. Consequently, ongoing iterative knowledge creation and especially the assessment, whether the implemented actions and decisions lead to climate resilience are crucial for further foundational decision-making processes.

However, indicators, measurement and evaluation should not give the impression that societies can control and continue to appropriate everything – the world, the social-ecological system – believing that there is no backlash. Instead, these instruments should be used and thought in such a way that, on the one hand, we can better understand the system, and on the other hand, and above all, we can begin to listen to the system, to the world again to have the ability to shape climate-resilient pathways.

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Appendices

Appendix A: Overarching and specific impact objectives

Table1: Overachingimpact objectives

Overarching impact objectives	Year	N	Mean	SD	Not at all im-portant	Not important	Rather unim-portant	Neither nor	Rather im-portant	Important	Very important
Building climate resilience networks on the ground	2019	58	5,14	1,75	5%	3%	9%	14%	21%	20%	29%
	2020	52	4,58	1,71	4%	12%	12%	15%	27%	15%	15%
Development of long-term guiding principles	2019	56	5,05	1,52	3%	3%	8%	19%	19%	33%	16%
	2020	52	5,63	1,39	2%	2%	6%	8%	13%	42%	27%
Transferable implementa-tion measures	2019	59	6,15	1,19	0%	1%	1%	7%	10%	22%	57%
	2020	53	6,26	1,08	2%	0%	0%	4%	8%	36%	51%
Initiation of long-term be-havioural change	2019	59	5,56	1,47	1%	4%	4%	12%	18%	28%	31%
	2020	50	5,26	1,65	2%	6%	8%	14%	18%	22%	30%
Integration of results into urban planning	2019	59	6,08	1,33	0%	3%	3%	7%	7%	21%	58%
	2020	52	6,23	1,20	2%	0%	2%	2%	15%	21%	58%
Sensitisation and aware-ness-raising of actors re-garding climate resilience	2019	59	6,15	1,13	0%	0%	4%	7%	9%	24%	55%
	2020	52	5,94	1,45	2%	4%	2%	2%	21%	19%	50%
Improvement of energy effi-ciency	2019	56	3,82	1,91	16%	17%	9%	20%	14%	16%	8%
	2020	50	3,38	2,04	30%	6%	20%	12%	12%	12%	8%
Early detection of extreme events	2019	53	3,62	1,88	13%	21%	15%	15%	15%	11%	10%
	2020	51	3,31	2,15	31%	18%	4%	14%	10%	16%	8%
Improvement of communi-cations between and with stakeholders	2019	58	5,91	1,19	0%	3%	0%	5%	23%	28%	42%
	2020	51	5,55	1,47	4%	0%	6%	8%	22%	31%	29%
Improvement of quality of life	2019	56	5,70	1,35	0%	3%	5%	9%	22%	23%	38%
	2020	53	5,79	1,28	0%	4%	2%	8%	21%	30%	36%
Improvement of resource efficiency	2019	57	4,35	1,75	8%	11%	14%	17%	20%	22%	8%
	2020	50	4,72	1,55	6%	2%	10%	22%	28%	20%	12%
Improvement of environ-mental quality	2019	56	5,14	1,71	2%	6%	14%	14%	9%	31%	23%
	2020	51	5,22	1,46	2%	4%	6%	14%	29%	24%	22%
Improvement of knowledge and information transfer be-tween actors on the ground	2019	59	6,08	1,21	0%	1%	3%	7%	9%	28%	51%
	2020	52	5,96	1,30	2%	0%	4%	4%	21%	23%	46%

Overarching impact objectives	Year	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Improvement of knowledge transfer between research and practice	2019	57	6,02	1,14	0%	2%	2%	8%	17%	29%	43%
	2020	53	6,23	1,01	0%	2%	0%	4%	11%	34%	49%
Further development of coping strategies for extreme events	2019	58	6,03	1,47	3%	3%	3%	3%	14%	15%	58%
	2020	53	5,79	1,52	4%	2%	4%	4%	17%	28%	42%

Table 2: Capacity Building - Specific Impact Objectives.
Ratings of the importance of potential specific objectives in projects addressing the impact sphere Capacity Building.

Capacity Building	Year	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Activation and mobilisation of actors	2019	37	6,49	0,77	0%	0%	0%	3%	8%	27%	62%
	2020	38	6,29	1,11	0%	3%	3%	0%	8%	32%	55%
Development of counselling services for the respective target group	2019	36	4,81	1,77	6%	3%	14%	25%	14%	14%	25%
	2020	37	4,70	1,66	3%	8%	19%	11%	16%	32%	11%
Development of decision-making aids approaches and recommendations for action	2019	36	6,11	1,06	0%	0%	3%	3%	25%	19%	50%
	2020	37	6,11	1,58	3%	3%	5%	3%	8%	14%	65%
Sensitisation and awareness-raising	2019	36	6,56	0,77	0%	0%	0%	3%	8%	19%	69%
	2020	38	6,53	0,80	0%	0%	0%	3%	11%	18%	68%
Strengthening self-empowerment and self-regulation	2019	36	5,42	1,36	0%	6%	6%	6%	31%	31%	22%
	2020	38	5,21	1,60	3%	5%	8%	11%	24%	26%	24%
Improvement of knowledge transfer	2019	36	6,14	0,87	0%	0%	0%	6%	14%	42%	39%
	2020	37	6,00	1,18	0%	0%	8%	3%	11%	38%	41%
Networking of actors	2019	36	6,22	0,99	0%	0%	3%	3%	14%	31%	50%
	2020	38	5,95	1,39	3%	3%	3%	0%	16%	34%	42%
Knowledge about coping strategies during extreme events	2019	36	5,86	1,29	3%	0%	0%	11%	14%	36%	36%
	2020	36	5,28	1,41	0%	3%	14%	11%	14%	42%	17%

Table 3: Management and Planning - Specific Impact Objectives.
Ratings of the importance of potential specific objectives in projects addressing the impact sphere Capacity Building.

Management and Planning	Year	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Development of decision-making aids, solution approaches and recommendations for action	2019	39	6,49	0,88	0%	0%	3%	3%	3%	26%	66%
	2020	29	6,14	1,68	7%	0%	0%	7%	7%	10%	69%
Integration of the results into the urban development programme	2019	39	6,21	1,22	0%	3%	5%	0%	8%	29%	55%
	2020	29	5,86	1,68	7%	0%	0%	10%	10%	21%	52%
Integration of the results into urban land use planning (Bauleitplanung)	2019	39	6,03	1,22	3%	0%	3%	3%	11%	45%	37%
	2020	29	5,66	1,59	3%	0%	7%	14%	10%	24%	41%
Integration of the results into urban development funding	2019	39	5,46	1,50	3%	0%	8%	16%	21%	18%	34%
	2020	29	5,21	2,14	10%	7%	3%	14%	7%	14%	45%
Integration of the results into the urban framework planning (Städtebauliche Rahmenplanung)	2019	39	6,08	1,11	0%	0%	5%	5%	11%	37%	42%
	2020	29	5,86	1,55	3%	0%	7%	7%	10%	24%	48%
Improving land provisioning & ensuring fresh air supply	2019	39	5,67	1,58	3%	3%	8%	5%	11%	32%	39%
	2020	29	4,79	2,19	14%	3%	14%	14%	0%	24%	31%
Improve land use planning with regard to open spaces that are important for climate ecology.	2019	38	5,92	1,36	0%	5%	3%	3%	11%	35%	43%
	2020	29	5,38	1,76	3%	0%	14%	21%	3%	17%	41%
Improving water retention & stormwater management	2019	39	5,49	1,32	0%	3%	8%	5%	29%	29%	26%
	2020	29	4,93	2,28	14%	7%	10%	7%	3%	21%	38%

Table 4: Behavioural Changes of Actors - Specific Impact Objectives.
Ratings of the importance of potential specific objectives in projects addressing the impact sphere Behavioural Changes of Actors.

Behavioural Changes of Actors	Year	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Activation and mobilisation of actors	2019	36	5,28	1,11	3%	0%	0%	17%	31%	44%	6%
	2020	30	6,07	1,51	3%	0%	7%	0%	17%	13%	60%
Contribution to increasing social stability	2019	34	3,82	1,64	12%	12%	15%	24%	24%	12%	3%
	2020	30	4,13	2,08	17%	10%	13%	10%	17%	20%	13%
Contribution to increasing economic stability	2019	30	3,20	1,58	20%	17%	17%	23%	17%	7%	0%
	2020	30	3,57	1,96	20%	20%	7%	13%	23%	10%	7%
Development of counselling services by the target groups	2019	33	4,30	1,26	3%	6%	12%	33%	27%	18%	0%
	2020	30	4,60	1,77	7%	10%	7%	20%	20%	23%	13%
Strengthening the self-determination and self-control of the actors	2019	34	4,74	1,11	3%	0%	6%	29%	35%	26%	0%
	2020	30	4,87	1,36	0%	0%	3%	37%	13%	30%	10%
Improvement of knowledge transfer between actors	2019	35	5,46	0,78	0%	0%	0%	11%	37%	46%	0%
	2020	30	6,00	1,29	0%	3%	3%	7%	7%	37%	43%
Behavioural changes in agriculture & horticulture	2019	25	2,92	1,55	16%	32%	20%	20%	4%	4%	4%
	2020	30	3,33	2,04	30%	10%	10%	23%	10%	7%	10%
Behavioural changes in dealing with extreme events	2019	34	4,94	1,28	0%	6%	6%	24%	24%	35%	6%
	2020	30	5,50	1,38	0%	7%	3%	7%	23%	37%	23%
Behavioural changes in how counselling services are used	2019	32	4,50	1,34	0%	13%	6%	28%	28%	22%	3%
	2020	30	4,53	1,61	3%	10%	13%	20%	17%	30%	7%
Interconnection of actors	2019	36	5,00	1,26	3%	3%	3%	22%	25%	42%	3%
	2020	30	5,70	1,62	3%	0%	13%	3%	7%	33%	40%

Table 5: Information and Communication - Specific Impact Objectives.
Ratings of the importance of potential specific objectives in projects addressing the impact sphere Information and Communication.

Information and Communication	Year	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Development of decision-making aids, solution approaches and recommendations for action	2019	38	6,50	0,89	0%	0%	3%	0%	11%	18%	68%
	2020	41	6,00	1,67	5%	2%	5%	0%	10%	20%	59%
Software tools for information and communication	2019	38	4,87	2,06	8%	13%	5%	11%	13%	21%	29%
	2020	41	4,85	1,80	5%	10%	7%	15%	22%	20%	22%
Improving communication within organisations (e.g. administration)	2019	38	5,87	1,02	0%	0%	0%	8%	34%	21%	37%
	2020	41	5,59	1,43	2%	2%	2%	7%	32%	20%	34%
Improving communication between organisations and external stakeholders	2019	38	6,24	0,94	0%	0%	0%	8%	11%	32%	50%
	2020	41	5,73	1,60	5%	0%	7%	2%	17%	27%	41%
Improving communication between stakeholders	2019	37	6,14	1,08	0%	3%	0%	3%	16%	32%	46%
	2020	40	5,73	1,43	3%	3%	3%	8%	18%	33%	35%
Improve dialogue between all actors in the project	2019	38	6,21	0,81	0%	0%	0%	3%	16%	39%	42%
	2020	41	5,73	1,48	5%	0%	2%	7%	15%	37%	34%
Improving knowledge transfer within institutions (e.g. administration)	2019	38	5,95	1,06	0%	0%	3%	5%	26%	26%	39%
	2020	41	5,68	1,44	2%	2%	2%	7%	24%	24%	37%

Table 6: Green Infrastructure - Specific Impact Objectives.
Ratings of the importance of potential specific objectives in projects addressing the impact sphere Green Infrastructure.

Green Infrastructure	Jahr	N	Mean	SD	Not at all important	Not important	Rather unimportant	Neither nor	Rather important	Important	Very important
Increasing climate resilience through green infrastructure	2019	42	5,86	0,61	0%	0%	0%	2%	19%	69%	10%
	2020	36	6,39	1,08	0%	0%	3%	6%	11%	11%	69%
Increasing the climate resilience of green infrastructure	2019	42	4,93	1,33	0%	7%	7%	19%	26%	33%	7%
	2020	35	5,37	1,68	3%	3%	9%	17%	14%	17%	37%
Strengthening the initiative of the actors regarding the use & improvement of the green infrastructure	2019	42	5,19	1,37	2%	5%	5%	10%	24%	48%	7%
	2020	35	5,74	1,34	3%	0%	0%	11%	26%	23%	37%
Improvement of fresh air supply through green infrastructure	2019	41	5,07	1,31	2%	2%	5%	20%	24%	39%	7%
	2020	36	5,61	1,38	0%	3%	6%	11%	25%	19%	36%
Improving awareness of green infrastructure among stakeholders	2019	42	5,62	1,01	0%	0%	7%	7%	12%	64%	10%
	2020	36	6,42	0,84	0%	0%	0%	6%	6%	31%	58%
Improving water retention & stormwater management	2019	42	5,07	1,11	0%	0%	12%	17%	29%	38%	5%
	2020	34	5,74	1,60	3%	6%	0%	6%	21%	21%	44%

Appendix B: Indicators for Monitoring Urban Climate Change Resilience and Adaptation (1st Contribution)

sustainability

MDPI

Article

Indicators for Monitoring Urban Climate Change Resilience and Adaptation

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Abstract: In the face of accelerating climate change, urbanization and the need to adapt to these changes, the concept of resilience as an interdisciplinary and positive approach has gained increasing attention over the last decade. However, measuring resilience and monitoring adaptation efforts have received only limited attention from science and practice so far. Thus, this paper aims to provide an indicator set to measure urban climate resilience and monitor adaptation activities. In order to develop this indicator set, a four-step mixed method approach was implemented: (1) based on a literature review, relevant resilience indicators were selected, (2) researchers, consultants and city representatives were then invited to evaluate those indicators in an online survey before the remaining indicator candidates were validated in a workshop (3) and finally reviewed by sector experts (4). This thorough process resulted in 24 indicators distributed over 24 action fields based on secondary data. The participatory approach allowed the research team to take into account the complexity and interdisciplinarity nature of the topic, as well as place- and context-specific parameters. However, it also showed that in order to conduct a holistic assessment of urban climate resilience, a purely quantitative, indicator-based approach is not sufficient, and additional qualitative information is needed.

Keywords: resilience; indicator; monitoring; climate change; climate adaptation

1. Introduction

Our society is facing multitudinous different challenges—in this paper we are focusing on two main challenges: climate change and urbanization. In 2015, 3.9 billion people were living in cities. By 2050, the population in cities is projected to reach up to 6.7 billion people [1]. Urban agglomerations will continue to grow and are increasingly threatened by the high uncertainty of climate change impacts [2]. In response to these impacts, cities are already implementing climate change adaptation measures in order to prepare for uncertain future changes. Adaptation to climate change and climate variability is not a new phenomenon [3]. However, steadily rising temperatures, increasing magnitude and frequencies of climate-induced extreme events, such as droughts, floods, storms or intense rainfall, as well as the growth of the global human population pose new adaptation challenges to humankind [3]. In our research, we use the term adaptation as defined by the United Nations Climate Change [4]: "Adaptation refers to adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change". Furthermore, the ability of adaptation is understood as part of resilience, as described by Folke et al. [5]. The concept of resilience can be attributed to Holling [6] and originates from ecology. He described resilience as the "measure of persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between population or state variables" [6]. The original concept of resilience gained increased importance in other disciplines, whereby the definitions of resilience were steadily differentiated, broadened and deepened. There are three main understandings of the character of resilience: "bounce back" which refers to the fast return to an equilibrium state of a system after a shock event, "bounce forward" which focuses on a system which should have capacities to be adapted to uncertainty and "both" which addresses the co-occurrence of the capacities for "bounce back" and "bounce forward" [7]. Meerow et al. [2] analysed 57 academic definitions of urban resilience, with particular regard to these fundamental understandings of urban resilience. The analysis showed that 35 definitions focus on "bouncing back", 15 on "bouncing forward" and only seven see both capacities as elementary for resilience. Figueiredo et al. [8] pointed out that the definitions shifted from an equilibrium-centred understanding of resilience towards an evolutionary/transformational understanding of resilience. Four main approaches to resilience can be identified: disaster risk reduction [9], socio-ecological [10], sustainable livelihoods [11] and the community-oriented approach [12]. Resilience can also be discussed on different scales (county, region, urban area, city, community and household) [8]. Even though it is important to take action on all scales, in this work we are focusing on cities—particularly in Germany—and are using the socio-ecological approach. Besides the definitions and understandings of resilience in academia, it is very important to also consider how practitioners interpret resilience. Practitioners and policy makers are a central part of the resilience-transformation process. Therefore, it is remarkable that the term resilience is interpreted in a much wider range of ways by practitioners than by academia [13].

Adaptation measures are implemented in different sectors of the city system. Since cities are complex and multifaceted systems, which in turn contain other systems, measuring the success of resilience-increasing activities poses a particular challenge. However, measurement is of great importance in order to be able to govern and steer the adaptation and transformation process. Every city has its specific context and needs, and its exposure to risk and vulnerability is dynamic and changes over time [8].

However, it is important to develop measurable indicators for different reasons. Indicators enable monitoring of the resilience-building process, as they provide regular and impartial feedback. They build an evidence base and make resilience more tangible for decision and policy makers as well as society at large. Furthermore, indicators can help to govern and steer the transformation process because they help to structure the new field of urban climate resilience. Clear indicators are not only important for the general measurement of resilience, but also for the analysis of whether adaptation measures were effective and whether the expected results were achieved [14]. Indicators also contribute to the credibility, transparency and accountability of the measures implemented. This in turn is very important for local policy makers to support further adaptation measures.

However, the development of indicators in this context poses particular challenges. In addition to the conceptual challenges of urban climate resilience, context specificity represents another challenge for the development of resilience indicators. Consequently, it is very important to consider how to include context specificity in the indicator set. Another fundamental consideration is in regard to the context-specific, dynamic and ever-changing nature of risk and vulnerability [8].

MONARES (monitoring of adaptation measures and climate resilience in cities), a project funded by the German Federal Ministry of Education and Research (BMBF), was initiated in order to address the main challenges of (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 and (3) the use of resilience and adaptation measurements. The aim of MONARES is to create application-oriented methodologies for monitoring and evaluating local adaptation measures. As we are focusing on the special needs for cities in Germany, we are working together with 14 other projects of the funding initiative "Climate resilience through action in cities and regions" of the BMBF, who are focusing on climate change adaptation measures and urban resilience, as well as doing on-the-ground research in municipalities across Germany. These projects and cities differ considerably concerning scale (street, district, city, suburbs and region), inhabitants and type of adaptation measure (e.g., planning, physical infrastructure, capacity building or greening). Important commonalities of the projects are their interdisciplinary approach, the aim to enhance urban climate resilience and that they conduct on-the-ground research. However, the projects test many different pathways to improve resilience, and MONARES is focusing on how to measure the success and impact of these different projects and activities with a common set of indicators. In order to ensure applicability, we began to involve the projects at an early stage of our research. The first key step (Figure 1 Phase 1) before developing the indicators was to develop a framework [15] to describe urban resilience. Based on 19 frameworks described in the literature [16–34], our first draft was developed, which then was modified together with the projects. This process was indispensable as it resulted in a definition of urban resilience that is suitable for all projects so that there was agreement on common basic principles.

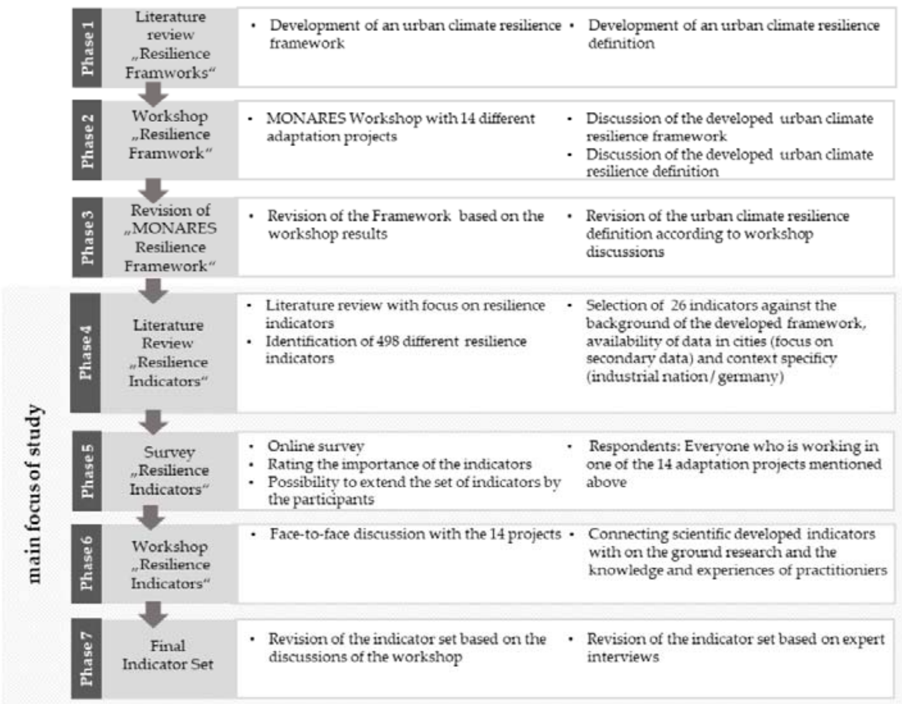

Figure 1. MONARES—research process.

Based on steps 1 to 3 as shown in Figure 1, the final definition of urban resilience in MONARES is as follows:

The climate resilience of a city depends on the ability of its sub-systems 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.

Based on this preliminary work, a four-step mixed-method approach (Figure 1 Phases 4–7) was designed to develop the indicators for urban climate resilience on which this paper focuses.

2. Materials and Methods

The exponential growth of literature concerning urban resilience contains a multitude of approaches, indicators and methods stressing the resistance of an urban system. The development of the method of this paper was guided by the questions: resilience for whom, for what and where [35]. A reflexive approach of input and feedback loops was developed in order to adapt and validate international indicators. A main challenge was to adapt the indicators to the specific context of German communities in the face of climate change.

2.1. Literature Review: "Resilience Indicators"

The selected frameworks (see Figure 1 Phase 1) were identified through an extensive literature review using the key search terms "resilience", "urban resilience", "climate resilience", "adaptive capacity + urban/city", "resistibility + urban" and "learning capacity + urban/city" (in German and English). Based on these frameworks and their operationalisation of resilience, an extensive list of indicators was deduced. These indicators were matched with the MONARES framework, developed in steps 1–3, which consists of dimensions and action fields (see Table 1).

Table 1. Dimensions and action field of the resilience framework.

Dimension	Action Field
Environment	Soil and green spaces
	Water bodies
	Biodiversity
	Air
Infrastructure	Settlement structure
	Energy
	Telecommunication
	Traffic
	Drinking and wastewater
Economy	Innovation
	Business
	Economic structure
Society	Research
	Knowledge and risk competence
	Healthcare
	Socio-demographic structure
	Civil society
	Civil protection
Governance	Participation
	Municipal budget
	Strategy, plans and environment
	Administration

As we have the aim to develop a user-friendly, applicable and transparent indicator set, we firstly reduced the indicators to two indicators per action-field. The two most important selection criteria were (1) context specificity of industrial nations, especially Germany, and (2) data availability. Context specificity is important because many of the indicators in the literature are suitable for the context of the Global South but not for the Global North, and even indicators that might be suitable for the Global North might not be suitable in the German context. The second criteria—data availability—is therefore important because municipalities have, on the one hand, good access to a lot of data but have, on the other hand, resource problems regarding time, finances and human resources. Action fields without literature-based indicators required the development of new ideas within the project. Given the available data, some action fields were difficult to measure without significantly neglecting the complexity of the action field.

2.2. *Survey to Assimilate the Indicators for Context Specificity*

Based on the literature review (see Figure 1 Phase 4) and the described selection process, an online-survey was developed (see Figure 1 Phase 5). The survey was used because, given that the indicators should be transparent and user-friendly, not only the scientific background is important, but a clear understanding of the indicators in the broad community is important also. The survey was sent to all persons who are working in one of the 14 projects mentioned above. 39 people answered the survey.

The main aim of the survey was to measure how participants assess the different indicators. They were requested to rate the importance of every indicator regarding urban climate resilience on a scale from one (low importance) to five (high importance). Each action field was represented by at least one indicator (Table 1). Besides the rating of indicators, the survey consisted of four chapters: First, some general background; Second, the context of urban climate resilience; Thirdly, the indicators; Fourthly, the possibility of extending the set of indicators by indicators without existing data sources, and some final remarks.

2.3. *Workshop Following the Survey*

As mentioned previously, the explanatory power of an indicator set of urban climate resilience is hugely dependent on the context, and therefore we discussed the results of the survey again with the 14 projects (see. Figure 1 Phase 6). Moreover, this feedback loop increases the transparency of the process and the robustness of the results. The workshop started with presenting the survey results and then the participants were split into two groups in order to create two independent feedback loops and cross-validation of the indicator set. For each group, a poster was prepared, listing all indicators included in the survey. The indicators that were ranked lower in the survey were written on the poster in light grey (compared to black), for an improved visualization of the survey results. Hence, both groups had the visual results to discuss and were asked to compare each pair in detail and find explanations for the survey results. In addition, the overall set remained visible, which allowed participants to keep the important question of the overall themes in mind. Therefore, indicators could be moved across the set or could become more important if they were deemed a missing piece in the mosaic. The guiding questions for this phase of the workshop were: (1) Are there enough indicators? (2) How many indicators are needed and sufficient? (3) Are the selected indicators the right ones or should they be changed? And (4) are there important gaps in the set that are yet to be filled?

2.4. *Finalizing the Indicators Set*

In Step 7 (see Figure 1) we analyzed the results of the workshop. Furthermore, expert interviews with practitioners were conducted with the aim to develop indicators in action fields where neither the literature review nor survey and workshop produced results. On this basis, we finalized the urban resilience indicator set.

3. Results

In our review of the academic literature, 19 indicator-based resilience frameworks were analyzed. Based on the indicators of these frameworks a list of 498 indicators (including duplicates) was generated. The indicator list was used as an important starting point for developing the MONARES Indicator Set (MIS). After screening the indicators through the lens of the MONARES-framework, some action fields remained empty and were filled by proposed indicators of the MONARES project-team. One to four indicators were selected per action field in order to cover all topics and include sufficient redundancy. Table 2 shows the selected and proposed indicators.

Table 2. Delineated indicators and action fields.

Dimension	Action Field	Indicator	Code	Literature
Environment	Soil and green spaces	Degree of soil sealing	A_a_1	[31]
		Land consumption	A_a_2	[21]
		Recreational area	A_a_3	[21]
	Water bodies	Share of water bodies	A_b_1	[36]
		State of water bodies	A_b_2	[23]
	Biodiversity	Share of nature conservation and protection areas	A_c_1	[23]
		Wetlands and retention areas	A_c_2	[36]
	Air	Cold air parcels	A_d_1	[23]
Infrastructure	Settlement structure	Density of buildings	B_a_1	[37]
		Accessibility of green spaces	B_a_2	[38]
	Energy	Share renewable energy	B_b_1	[18]
		Diversity renewable energy	B_b_2	[18]
	Telecommunication	Broadband access	B_c_1	[37]
	Traffic	Concept for sustainable traffic	B_d_1	[21]
	Drinking and wastewater	Number of springs	B_e_1	[8]
Economy	Innovation	Innovation index	C_a_1	[37]
	Business	Ratio of insolvencies to start-ups	C_b_1	[22]
	Economic structure	Share of employees in largest sector	C_c_1	[39]
		Employees in research intensive companies	C_c_2	[40]
Society	Research	Number of research projects	D_a_1	[18]
	Knowledge and risk competence	Citizen information about heat, heavy rain and flooding	D_b_1	[37]
		Experience with extreme events in last five years	D_b_2	[37]
	Health care	Accessibility of hospitals	D_c_1	[41]
		Doctors per 10,000 citizens	D_c_2	[40]
	Socio-demographic structure	Share of citizens ABV6/U65	D_d_1	[42]
		Share of employees	D_d_2	[30]
	Civil society	Voter turnout	D_e_1	[42]
		Number of associations	D_e_2	[42]
	Civil protection	Fire brigade	D_f_1	[37]
		Citizens in honorary positions	D_f_2	[31]
Governance	Participation	Number of participation processes	E_a_1	[37]
		Contact point for participation	E_a_2	[37]
	Municipal budget	Depth per citizen	E_b_1	[21]
		Tax income	E_b_2	[21]
	Strategy, plans and environment	Risk and vulnerability analysis	E_c_1	[26]
		Strategies against heavy rain and heat in plans	E_c_2	[26]
		Landscape plan legally binding	E_c_3	[37]
		Climate change adaptation part of urban development plan	E_c_4	[30]
	Administration	Inter-office working group regarding risk, climate change and resilience	E_d_1	[37]
		Climate manager	E_d_2	[37]

3.1. Survey about Resilience Indicators

The survey was structured based on the results of Phase 4. The survey (Figure 1 Phase 5) was filled out by 39 respondents within the funding initiative "Climate resilience through action in cities and regions" of the BMBF. The overall mean perceived importance of the indicators was 3.63 within the complete range from one to five. Considering the complexity of the urban system and the interdisciplinary character of the indicator set, this rating was regarded as high. The median of four was also high. The standard deviation of 1.17 together with the entire evaluation range reflected the diversity of interpretations. Nevertheless, despite this diversity, these core numbers show that the indicators were overall judged as important. Splitting the indicators into the five main dimensions (Figure 2), the median shows that only the indicators within the dimension of economy were rated less important, they are rated in the middle of the range, which might indicate a slight indecisiveness. Several reasons could explain this, such as that the indicators selected were not covering the dimension in a satisfactory manner or that the dimension is perceived as unrelated to urban climate resilience. Those questions were discussed in the workshop (Figure 1 Phase 6) in detail.

Figure 2. Median importance of indicators grouped into five dimensions.

All top five ranked indicators had a median rating of 5. The mean values ranged from 4.4 to 4.6. Only two respectively three respondents did not rate the indicators, showing the general agreement regarding the importance. Nevertheless, regarding the minimum values, all had a large range from 2 to 5.

The set of five indicators in Table 3 shows that the three dimensions *environment*, *governance* and *society* were seen as particular important. The indicator rated as the most important was the environment indicator *cold air parcels*. Second and fourth ranked were *governance* indicators, namely *inter-offices working groups regarding risk, climate change and resilience* and *strategies against heavy rain and heat in plans*. Third and fifth ranked were two indicators from the dimension *society*. The respondents saw the importance of *experience with extreme events in the last five years* and *citizen information about heat, heavy rain and flooding* as particularly crucial for building urban resilience.

Table 3. The five indicators rated as most important in the survey.

Dimension	Action field	Indicator	Min.	1st Quartile	Median	Mean	3rd Quartile	Max	N/A
Environment	Air	Cold air parcels	2	4	5	4.6	5	5	3
Governance	Administration	Inter-offices working group regarding risk, climate change and resilience	2	4	5	4.5	5	5	2
Society	Knowledge and competence	Experience with extreme events in last five years	3	4	5	4.5	5	5	3
Governance	Strategy, planned and environment	Strategies against heavy rain and heat in plans	2	4	5	4.5	5	5	3
Society	Knowledge and competence	Citizen information about heat, heavy rain and flooding	2	4	5	4.4	5	5	2

Table 4 displays the five lowest ranked indicators in context of their relevance related to urban climate resilience. The overall lowest rated indicators were both from the *society* dimension, namely *voter turnout* and *number of associations*. The respondents did not think that they were relevant for measuring and monitoring urban resilience. The third lowest indicator was the *infrastructure* indicator *broadband access*. Fourth and fifth were two *economic* indicators measuring *ratio insolvencies to start-ups* and *share employees in largest sector*.

Table 4. Five lowest rated indicators.

Dimension	Action field	Indicator	Min.	1st Quartile	Median	Mean	3rd Quartile	Max	N/A
Society	Civil society	Voter turnout	1	2	3	2.4	3	4	1
Society	Civil society	Number of associations	1	2	3	2.6	3	4	2
Infrastructur	Telecommunicatior	Broadband access	1	2	3	2.8	4	5	3
Economy	Business	Ration insolvencies to start-ups	1	2	3	2.8	3.5	5	4
Economy	Economic structure	Share Employees in largest sector	1	2	3	2.8	3	4	6

Figure 3 displays boxplots of all indicators. The main tendency has already been shown in a more condensed form previously in Figure 2. *Share of nature conservation and protection areas (A_c_1)* was the lowest ranking in the dimension *environment*. The second indicator of the action field *biodiversity*, however, received high approval, which emphasised the perceived importance of *biodiversity* considerations for climate resilience in the urban context. *Settlement structure* (B_a_1&2) was seen as vital for structural climate change adaptation, similar to the first action fields of *soil and green spaces* (A_a_1-3).

Energy (B_b_1&2) indicators, in contrast, not only ranged from a rating of one to five, but the quartiles of the boxplot also show a comparably high range around the middle of the scale.

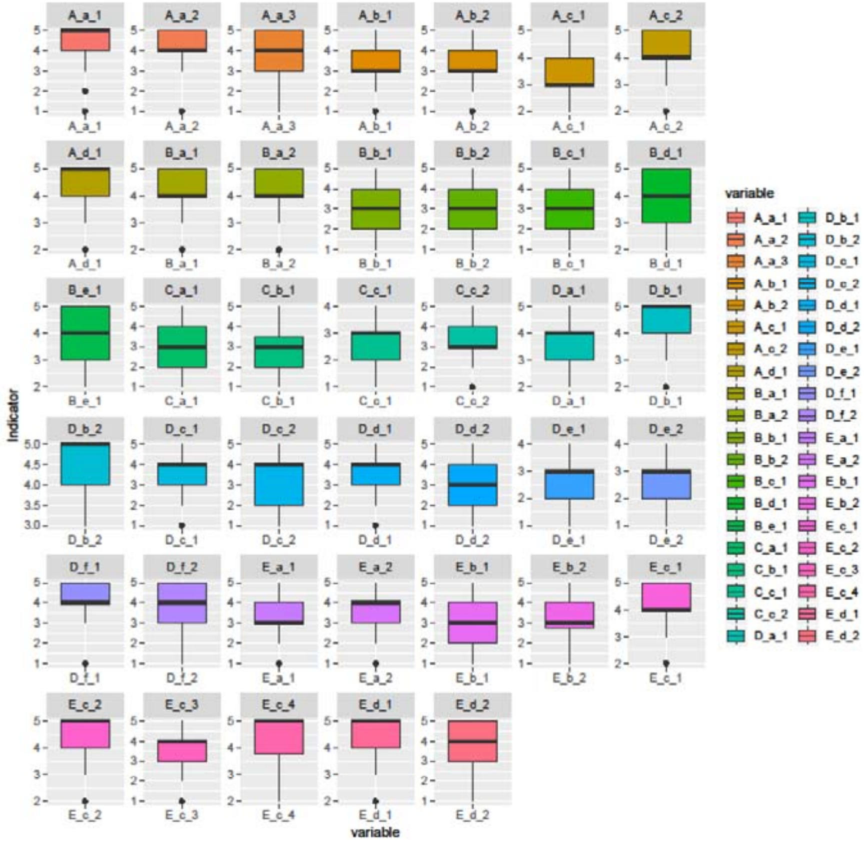

Figure 3. Box-plots of all indicators included in the survey (see Table 2 for indicator codes).

3.2. General Workshop Results Regarding the MIS

The discussion of the indicators during two discussion groups yielded important feedback on the overarching attributes and requirements of the MIS. They were mentioned several times from different persons and related to different indicators. Firstly, one important aspect was the size of the municipality and hence the scaling of the indicator. No universal scaling was found appropriate, since the different units and scales required indicator-specific scaling. Nevertheless, the scaling was seen as an important factor in order to reach the goal of acquiring indicators for municipalities and therefore an interpretable result on this level of administrative organization.

The overall discussion about applicability and feasibility was touched on in many ways from different angles, most prominently regarding data availability, numbers of indicators and total effort needed. The balancing of the loss of information related to simpler indicators or vice versa with more complex indicators with higher explanatory power but with an infeasibility to be handled by the target group was seen as a key challenge. Therefore, the participants agreed that the indicators should be based solely on existing data, thereby reducing the overall effort and simplifying the calculations and data management.

The idea of detailed factsheets describing the data source and calculation of the indicator and helping with the interpretation of the result was raised by participants and received wide support. Factsheets also help to communicate the meaning of an indicator to uninitiated persons, which was also mentioned as a crucial aspect.

The total number of indicators to be feasible was seen at around 25. Certain gaps were identified during the workshop due to the fact that specific expertise related to certain action fields was missing in the room, specifically regarding the action fields *energy*, *wastewater* and *civil protection*. Here, single expert interviews were carried out after the workshop to fill in the gaps.

3.3. Indicator Specific Workshop Results

Table 5 summarizes the process of indicator development during the three phases of the survey, the workshop and ending in the final set of indicators. The indicators highlighted in grey are those of the initial indicator set that were seen as important by survey respondents and therefore stayed on the list. The indicators highlighted in orange were updated or modified as a result of the survey and/or workshop. The yellow indicators were moved from one action field to another. The indicator *degree of soil sealing* was inverted to *degree of unsealed ground*, as sealing is not per se negative, even may even be desirable or unavoidable in urban areas. The *cold air parcels* was seen as an important factor of resilience but should be updated, adding cold air streams to the indicators. *Biodiversity* was discussed in contradictory ways, as it was not clear to the participants how it is related to climate hazards. Hence, the workshop resulted in representing urban biodiversity with the indicator *wetland and retention areas* in order to include flood protection arguments into the indicator of biodiversity.

Infrastructure was seen undoubtedly as a key area for achieving urban climate resilience, but also related to secondary data and its inherent complexity most difficult to quantify currently. *Accessibility of green spaces* was rather seen as an indicator of social justice and less as a settlement structural indicator and hence the second indicator *building density*, slightly lower ranked in the survey, was included instead. The *share of renewable energy* indicator focused strongly on climate protection and less on resilience factors, such as robustness and redundancy. These factors were seen to be better covered by the *diversity of renewable energy sources*. However, it was also argued that even conventional energy should be included in the indicator. This observation was followed by the consideration that no climate resilience can be achieved without climate protection in the long term. Therefore conventional energy sources cannot be regarded as a positive contribution to climate resilience in the long term. The action field of *telecommunication* was deleted in accordance with the participants' perception of this as being less important than the other action fields, lacking data and having low to no influence of the municipality. Instead, the action field *wastewater treatment* was included, as there was agreement on its importance additionally to the supply side. No specific indicator was defined in the workshop due to missing competence in this regard. *Transportation* was discussed as an important action field for municipalities, but participants agreed that its complexity cannot be covered by one indicator. Therefore, the action field remained as an action field of the framework, reminding of the importance of the topic and urging municipalities to consider and discuss it qualitatively.

The discussion around the *economic* dimension reflected the lower ranking of its indicators in the survey. The dimensions *environment* and *infrastructure* were seen to be more naturally linked to resilience than the *economic* dimension. Nevertheless, discussing the importance of a resilient economy for an urban system generated acceptance for the dimension and its components. This example illustrates one very important lesson of the workshop: the need for explanation and building a common understanding. *Innovation* was seen to be covered best by the *number of employees in research intensive companies* not by the *innovation index*. The *tax income from companies* was considered an important resource for the financial ability of the municipality to adapt. This indicator was part of the action field *municipal budget* in the survey and has since been moved to *business*. Similar to *energy*, a *diverse economy* was considered more robust, flexible and redundant when facing uncertainty of climate impacts. It was also discussed whether there might be sectors with crucial or higher relevance than others, but the group agreed that no single sector could be selected.

There was a general agreement on the importance and contribution of *society* to urban climate resilience, but less agreement on how to measure it quantitatively. Literature shows that the experience with extreme events contributes positively to citizens' resilience. In addition, *citizen information about heat, heavy rain and flooding* (Table 3) was amongst the top five rated indicators. However, regarding the spatial scale of municipalities, it was argued that information is not only provided by the local authority and therefore the indicator was not further considered. *Civil society* started an intense discussion on how to measure it and if the proposed indicators were adequate. In contrast to the survey, where the indicator *voter turnout* ranked higher, the workshop participants disliked this indicator, arguing that *voter turnout* nowadays cannot be seen as a proxy indicator for solidarity and community in Germany. The indicator *associations* was also critically reflected upon as being unable to capture *civil society* entirely. Still, the participants were in favour of the imperfect indicator *associations* instead of deleting the action field. In the survey, the dimension *governance* and its indicators were ranked high, and this result was confirmed in the workshop. Only one change was decided: replacing the *contact point for participation processes* with the *number of conducted participation processes*. Both were ranked very close in the survey with a mean of 3.3 and 3.4, respectively.

Table 5. Indicator set after the survey, workshop and final set.

Dimension	Action Field	Survey Result	Workshop	MIS
Environment	Soil and green spaces	Degree of unsealed ground	Degree of unsealed ground	Degree of unsealed ground
	Water bodies	State of water bodies	State of water bodies	State of water bodies
	Biodiversity	Wetlands and retention areas	Wetlands and retention areas	Nature conservation and protection areas
	Air	Cold air parcels	Cold air parcels and flows	Ventilation status
Infrastructure	Settlement structure	Accessibility of green spaces	Building density	Building density
	Energy	Share renewable energy	Diversity of renewable energy	Diversity of renewable energy
			Per capita energy consumption	Per capita energy consumption
	Water supply and wastewater treatment	Number of springs	Number of springs	Number of springs
			(Including wastewater indicator)	Adapted sewer system
Economy	Innovation	Innovation index	Employees in research intensive companies	Employees in research intensive companies
	Business	Ration insolvencies to start-ups	Commercial tax per capita	Commercial tax per capita
	Economic structure	Employees in research intensive companies	Diversity of business	Diversity of business
Society	Research	Number of research projects	Number of research projects	Number of research projects
	Knowledge and risk competence	History with extreme events	History with extreme events	History with extreme events
	Health care	Accessibility of hospitals	Accessibility of hospitals	Number of doctors
	Sociodemographic structure	Share of citizens ABV6/U65	Share of citizens ABV6/U65	Share of citizens ABV6/U65
	Civil society	Voter turnout	Associations per 10000 capita	Associations per 10000 capita
	Civil protection	Fire brigade	Fire brigade	Fire brigade volunteers
Governance	Participation	Contact point for participation	Number of participation processes	Number of participation processes
	Municipal budget	Depth per citizen	Depth per citizen	Depth per citizen
	Strategy, plans and environment	Risk and vulnerability analsysis	Risk and vulnerability analsysis	Risk and vulnerability analsysis
		Strategies against heavy rain and heat in plans	Strategies against heavy rain and heat in plans	Strategies against heavy rain and heat in plans
	Administration	Inter-offices working group regarding risk, climate change and resilience	Inter-offices working group regarding risk, climate change and resilience	Inter-offices working group regarding risk, climate change and resilience
		updated	switched action field	no change

3.4. Urban Climate Resilience Indicator Set

Since even the diverse group of participants of the workshop did not cover all topics of the indicator set, experts were interviewed. Furthermore, the results of the survey and the results of the workshop were summarized and merged.

The final set of indicators is shown in Table 5 in the column MIS. Compared with the workshop set, the action field of *biodiversity* was seen crucial in its own right and better approximated by the indicator *nature conservation and protection areas*. Moreover, wetlands and retention areas were already covered by the *state of the water bodies* in line with the European Water Framework Directive regarding good ecological and chemical status. Hence, in order to create a balanced set of indicators, it was seen that the latter indicator added thematically more information and another aspect to the overall set. Secondly, the *air* action field was further developed, as *cold air parcels and flows* was difficult to interpret. The simple number or share of cold air parcels and streams were not clearly related to resulting air status. The *ventilation status* including the effects of air streams and cold air production parcels was therefore selected. For the *wastewater* action field introduced by the workshop, an expert interview recommended the indicator *share of adopted sewer system*. Another interview was conducted with the lower civil protection agency. The interviewee stressed the importance of volunteers across organizations, but as no data were gathered assessing the total numbers of volunteers, the most important one of the fire brigade was considered. Moreover, the municipality may have to consider this important topic even more in the future, as the principle of volunteers may be endangered due to demographic development. Finally, yet importantly, the *accessibility of hospitals* was interchanged with the *density of doctors*.

4. Discussion

The results from the work on indicators for monitoring urban climate resilience presented above yields a number of important insights and implications—with respect to previous studies but also for future research and for practitioners in this field.

Existing indicator sets are a good starting point, but adapting and extending them for the context at hand is crucial. There are numerous indicator sets for urban resilience; these provided a good basis from which the MONARES indicator set could be developed. However, many of the indicators analysed in the literature review were aimed at the context of developing countries. To adapt indicators identified in the review for the German context, four steps were important: (A) Disregarding indicators that do not allow sufficient distinction between cities, e.g., literacy rate is favoured as an indicator in many sources, but in Germany the literacy rate is rather high and differences between cities are marginal. (B) Disregarding indicators for which the data availability was rather limited in Germany. (C) Adding new indicators for action fields that are deemed important in the context of MONARES but which were not touched upon in the literature. (D) Focusing on municipalities as the key player for climate change adaptation. These level of municipalities require the set to be manageable in terms of data availability as well as size and complexity of the calculations.

Step A did not pose any major difficulties. Further, step B based on research concerning data availability did not cause problems. However, step C and D need to be examined in more detail.

First, the workshop clearly stated here the conflicting goals when discussing single action fields. It was felt that one indicator does not reflect the entirety of the topic, but at the same time all action fields were considered important and the total number of indicators should not exceed around 20, in order to stay manageable, which is far less than the proposed 52 indicators by the City Resilience Index (CRI) [22] and comparable to the core of 14 by the project Building Resilience Amongst Communities in Europe (embrace) [37] or Cutter's [43] core of 22. Since researchers, as well as practitioners, participated in our workshop, we had the impression that researchers tended to prefer larger, encompassing indicator sets. Compared with the scientists, practitioners were more in favour of concise and compact sets. The discussions in the workshop showed that persons with a research background had numerous ideas for new indicators for all dimensions, and advocated for their inclusion. During the workshop and its aftermath, practitioners working in municipalities displayed a different tendency—their perspective tended to focus more on how to handle the indicators in practice. Hence, what some researchers considered a concise indicator set was perceived by practitioners as overwhelming and too extensive. In order to find an adequate balance between a broad coverage and good usability in practice, it is important to involve both researchers and practitioners in the development of an indicator set. This finding is consistent with the literature and is one strength of the current study. Meerow and Stults [13], for example, stress the need for including practitioners in the process. Consequently, the trade-off between practicability and completeness had to be balanced, leading to the fact that some indicators that were considered important were still sorted out in order to cover all action fields and still achieve a manageable amount of indicators.

Second, it was mentioned that the indicators just by title were not clear in terms of their effect on and relation to urban climate resilience, and were consequently rated around the middle. This fact was considered while developing the survey, but an in-depth explanation of indicators was removed from the survey in favour of including more indicators covering all action fields and in consideration of the time needed to fill out the survey. However, this lack of explanations meant that the disciplinary background of respondents affected the ratings.

Third, indicators from the dimension *environment* were met with relatively high consensus while indicators from the dimension *economy* were faced with more diverging opinions. The indicator selection was dependent on the conceptualization of urban resilience and the urban context. The results contribute to the gap between the understanding of urban resilience by scholars and practitioners [13]. This became apparent both in the survey and the workshop and shows that more research is warranted on what characterizes a climate resilience urban economy. Supporting evidence for this can be taken from the fact that much more has been published on climate resilience and environmental issues than on climate resilience and economic issues. Moreover, this discussion displayed the importance of a negotiation-focused approach for defining place-specific attributes of urban resilience and its measures [44].

Fourth, secondary data was seen as crucial for monitoring purposes in order to reduce resource expenditure by the administration. In other words, "The best indicator is inoperable if there is no feasible way to obtain the required data." [37]. Moreover, there was a strong request from the local administrations for more provision of data from the higher administrations. They argued that data handling, data collection and finances for these activities are lacking. They stressed the need for data provision to be handled at the higher level of administration to avoid scaling and data comparability issues. Hence, data availability for indicators on a municipal level is a strong limiting factor, especially when it comes to indicators concerning infrastructure and social aspects [45]. Parts of the infrastructure related to energy, transport and communication are owned or organized by entities on a higher administrative level, such as the national government or by private entities. This tends to lead to limited data availability when it comes to data with a sufficient resolution on a municipal level. Here it would be favourable if entities in charge of the respective infrastructure made access to data easier and provided data with a resolution that is suitable for analyses on a municipal level. Moreover, the discussion centred around technical measures and physical impacts and less about social drivers and demographic changes. The latter are seen as core aspects of the community's ability to resist unforeseen threats. Nevertheless, the intense discussion around the proxies suggested by literature displayed vividly the intricacy of social dynamics. New data and methods from the higher administration or crowd-sourced databases are needed to better understand and monitor the indicators [43].

Fifth, it is important to mention that a conflict of goals among indicators can arise and can lead to a competition for the scarce resources. These reciprocal processes cannot be completely avoided. For example: impervious surfaces are seen negative regarding heavy rain, fresh air and heat island effects, but they are necessary for a redundant infrastructure and other urban functions. Another example is provided by Meerow and Newell [35] who analysed the negative correlation of park access and stormwater management goals, concluding that resilience measures create winners and losers. This also requires transparency of the data and the method of the indicator definition to understand the root causes of the conflicting goals and find adequate solutions. Here the Rockefeller [22] approach seems like a black box because it is difficult to deduce what adaptation measures are used as a data basis, and indicator calculations are unclear. During the workshop, several practitioners mentioned consequently the necessity of transparency and the need for precise communication and non-scientific language.

Sixth, following the previous point, many indicator approaches are used to build a composite index for resilience [19,22,45–47], vulnerability [18,48–52] or risk [53–55]. Specifically, at the scale of urban resilience, indexing across the multitude of action fields was discussed critically. The different scales, topics and units appeared to not be logically linkable. Moreover, a combined index value was seen to not tell much about the level of resilience. It was seen as more important to see the contribution of each action field to the overall resilience. Also, considering the next step of adaptation measures, it is more relevant to have a resilience profile displaying specific topics to be addressed in the municipal context.

Working at the science-policy interface was challenging for all sides. The mixed method approach proved invaluable in finding a common language, tolerance and understanding. This created an environment that allowed for constructive criticism, which is indispensable for finding a compromise.

5. Conclusions

In this study, we developed an indicator set to measure and monitor urban climate resilience for municipalities, thereby assessing the requirements of indicators and implementing a method for adapting global approaches to the local context.

The mixed method approach proved to be essential for the process of indicator development. It provided an adequate frame and time to develop a mutual understanding across disciplines, researchers and practitioners, which is needed in order to select indicators or accept indicators from different fields of expertise. Transparency in the process and the inclusion of feedback builds acceptance and trust. The concept of resilience provided the required assembly hall and saw climate change as the imperative. Even the often-criticized ambiguity of the resilience concept was helpful as it created room for discussion. The number of 24 indicators based on secondary data balanced as well as possible the diverging interests. Amongst the indicators, conflict of goals is unavoidable. Making the conflicts visible is a helpful basis for making informed decisions, which is a strength of this indicator set. In general, the softer and more qualitative aspects of resilience are challenging. They were seen as crucial but very hard to assess by quantitative proxies based on secondary data. Still, representative surveys to cover them in more detail on a regular basis were rejected by municipalities as too expensive and labour-intensive.

Developing an indicator set tends to be easier than assessing the significance or validity of an indicator over time and it requires an extended period of observations to be able to make statements about the significance of a certain indicator. Nevertheless, in order to advance this field of research, it is necessary to pursue this path and start inquiries into the significance or validity of the numerous indicators that are permeating the ongoing discussions. In further research, the indicators need to be tested in reality, and there needs to be more research that addresses the validation of the indicators.

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Appendix C: Regional climate resilience index: A novel multi-method comparative approach for indicator development, empirical validation and implementation (2nd Contribution)

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Original Articles

Regional climate resilience index: A novel multimethod comparative approach for indicator development, empirical validation and implementation

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ABSTRACT

High uncertainty in the occurrence of extreme events and disasters have made resilience-building an imperative part of society. Resilience assessment is an important tool in this context. Resilience is multidimensional as well as place-, scale- and time-specific, which requires a comprehensive approach for measuring and analysing. In this regard, composite indicators are preferred, and extensive literature is available on resilience indices on all spatial and temporal scales as well as hazard-specific or multi-hazard related indicators. However, transparent, robust, validated and transferable metrics are still missing from the scientific discourse. Hence, the research follows a novel composite index development approach: First, to develop and operationalise climate resilience on the county level in the state of Baden-Württemberg, Germany; second, to develop multiple composite indices in order to assess the impact of the construction methodology to increase transparency and decrease uncertainty; third, validating the index by statistical as well as empirical data and machine learning models - which is a novel endeavour so far. The results underscored that the two-step inclusive validation of data-driven statistical analysis in combination with empirical data proved to be essential in developing the index during the selection and aggregation of indicators. The results also highlighted a lower climate resilience of rural regions compared to metropolitan regions despite their better environmental status. Overall, machine learning proved to be essential in understanding and linking indicators and indices to policy, resilience and empirical data. The research contributes to a better understanding of climate resilience as well as to the methodological construction of composite indicators.

1. Introduction

Uncertainty in the occurrence of climate change-related extreme events and disasters is growing. The need to deal with this uncertainty has made resilience-building an imperative part of society. Therefore, the application and development of resilience assessment is an essential tool to better understand, identify and deal with these multi-dimensional and complex challenges.

Typically, composite indicators are used for the assessment of many multidimensional phenomena and intend to capture all facets. Over the last decade, literature references on composite indicators grew exponentially (Greco et al. 2019). However, composite indicators are highly criticized, with three major objections cited against them: a) they can send misleading and non-robust messages, b) they are not objective as judgement is included in selecting indicators, c) the amount of data needed is increased, which leads to difficulties in applying the indicators (Saltelli 2007). The construction of indices is often implemented either by solely data-driven approaches criticized for neglecting the phenomena or purely reasoning-driven approaches refusing statistics. Despite this criticism, two main reasons are responsible for their apparent popularity and common use for complex issues: Firstly, they can provide a simple picture, enable comparison and evaluation of complex multidimensional phenomena; secondly, they can function as drivers for behavioural change of governments or agencies (Becker et al. 2016). Therefore, composite indicators became increasingly popular in the complex realm of natural hazards.

Composite indicators have been developed on different scales (e.g., global, country, urban, household, individual) for risk (Welle and Birkmann, 2015; Birkmann and Welle, 2016; Marin-Ferrer et al., 2017), vulnerability (Welle et al., 2014; Depietri et al., 2013; Sorg et al., 2018;

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Table 1
Methodology - Concept.

STEP	SUBSTEP	CALCULATIONS
1. Spatial scale & initial indicators	1. Definition of the spatial scale	
	2. Upscaling from urban resilience to regional resilience	
	3. Development of the initial indicator set	
	4. Transformation of the initial indicators (normalization)	a. min–max-transformation
2. Validation of indicators	1. Empirical validation	a. Machine learning (random forest)
3. Aggregation of the index	1. Aggregation of the index	equal weights (eqw)
		mixed equal hierarchical weights (hw)
		Wroclaw Taxonomic
		Mazziotta-Pareto-Index (mpi)
4. Calculation of robustness & sensitivity	1. Reliablity	a. Cronbachs alpha
		b. Guttman's Lamda
	2. Global sensitivity analysis	a. Bayesian approach
5. Validation of aggregation method	1. Empirical validation	a. Non linear & non parametric correlation
6. Application of the index to the spatial scale	1. Application of the final index to the Federal State of Baden-Wurttemberg (Germany)	
	2. Analysis of the regional climate resilience of the counties of Baden-Wurttemberg	

Karagiorgos et al., 2016; Balica et al., 2009; Jamshed et al., 2019; Cutter et al., 2003) and resilience (Cutter et al., 2010a, 2014; ARUP and Rockefeller Foundation, 2014; Suárez et al., 2016; Keating et al., 2014). However, the criticism mentioned above is addressed less in the scientific discourse.

Present extreme events and disasters are increasing uncertainty, and major efforts are put into researching trends, scenarios and models. In light of this uncertainty, resilience is a positive as well as an interdisciplinary concept which is first defined in ecology by Holling (1973). According to Holling (1973), resilience is a "measure of persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationship between population or state variables". Many frameworks have been developed following Holling's work to evaluate resilience, but there is neither an agreed set of variables nor a comprehensive definition. Moreover, frameworks are established for specific threats and only some are considering climate change (ARUP and Rockefeller Foundation, 2014; Welle et al., 2014; Riedel et al., 2016; United Nations Office for Disaster Risk Reduction (UNISDR), 2017; Morrow, 2008; NOAA, 2015; Tyler and Moench, 2012; United Nations Development Program (UNDP), 2013) whereas in others it is not explicitly targeted (Birkmann et al., 2012; Béné et al., 2015; Renschler et al., 2010; Poland, 2008; Oregon Seismic Safety Policy Advisory Commission, 2013; Yoon et al., 2016). Some approaches are developed to focus on the resilience against specific hazards such as earthquakes (Poland, 2008; Oregon Seismic Safety Policy Advisory Commission, 2013), while others see resilience more generally and consider it is addressing multiple hazards (Cutter et al. 2008).

Besides the specificity of resilience to a particular hazard, resilience depends on the objective, the spatial scale, the temporal scale and the place (Meerow and Newell 2019). Stating the importance of scale and place in measuring resilience, assessment tools need to pass through a scaling process. For connecting resilience monitoring and adaptation measures, it is crucial to consider the scale and country-specific administrative duties. Authorities can only implement measures in the field of their legal competences, which is defined by the legal structure of the state. Therefore, indicators have to measure these areas of competence in regard to resilience that authorities can deduce, implement and evaluate adaptation measures. With the aim to transfer an already existing indicator set on a lower (e.g. urbane) scale to a higher (e.g. regional) scale, an upscaling process - including the mandatory duties of the scale-responsible authorities as well as testing reliability and validation - is needed. Upscaling has the advantage that the overall country-specific themes and challenges of climate change are already considered.

This study uses the case of the federal state of Baden-Württemberg, Germany. Regional climate resilience is not yet defined in Germany, however, urban climate resilience was defined within the German research project MONARES (www.monares.de). Hence we are using the following definition of urban climate resilience as a starting point for the upscaling process: "the climate resilience of a city depends on the ability of its sub-systems 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" (Feldmeyer et al. 2019).

The main aims of the research are 1. upscaling of urban climate resilience; 2. addressing the criticisms of composite indicators by testing four different aggregation methods and implementing a twofold validation as well as robustness and sensitivity analysis; 3. filling the gap of empirical validation of resilience measuring approaches (Bakkensen et al., 2017; Burton, 2015); 4. developing an indicator set for regional climate resilience.

2. Methodology

The methodological concept is divided into five major parts (see Table 1). The first step includes the definition of the spatial scale (Step 1.1), the upscaling of urban climate resilience to adequately resemble regional resilience (Step 1.2), selection of the initial indicator set (1.3) and the normalisation of all chosen indicators (1.4). Secondly, the indicators of Step 1 are validated using the machine learning package "RandomForest" (Step 2). Based on the outcome, the indicator set is updated accordingly. In Step 3, an index is constructed by applying different aggregation methods (Step 3.1. a.-d.) in order to understand the method's influence on the results. Subsequently, the reliability (Step 4.1) of both the indicators and index is tested, and a sensitivity analysis (Step 3.2) is executed. In Step 5, a validation for the aggregation methods, based on non-linear and non-parametric correlation, is applied. Eventually, the final index is applied to the federal state and a spatial analysis is conducted (Step 6).

2.1. Spatial scale and initial indicator set

The spatial scale is important because of the context- and space specificity of climate resilience. Due to the decentralized structure of the Federal Republic of Germany, each administrative level has specific responsibilities resulting in the freedom to adapt to the local characteristics. Therefore, climate resilience cannot be assigned to a single scale only. All levels of administration have responsibilities for

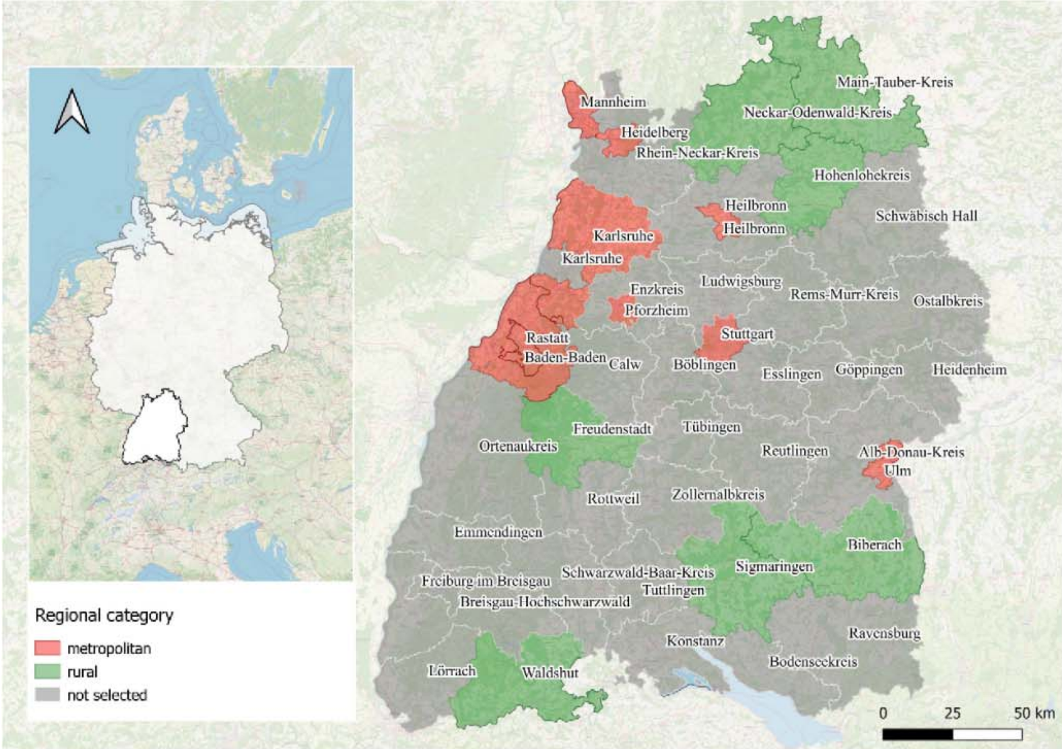

Fig. 1. Map of counties of Baden-Württemberg and selected sub-set for rural-metropolitan comparison.

influencing spatial climate resilience. Additional interdependences between scales, up- and downwards, influence the selection of indicators since the effect can be local but the cause regional.

In Step 1.1. the spatial scale is defined. This case study is focused on the regional scale and uses the Federal State of Baden-Württemberg as an example. Baden-Württemberg is divided into four districts, twelve regions and 44 counties (Fig. 1). 69% of the land area of the Federal State of Baden-Württemberg is covered by rural areas (landwirtschaft-bw, 2019). Each region has a regional planning authority. In total, there are 1,101 municipalities, some of which established municipal associations to execute their administrative affairs jointly.

Step 1.2. focuses on the upscaling process from urban to regional resilience. The starting point for the regional climate resilience index were the urban climate resilience indicators developed by Feldmeyer et al. (2019). The process included the upscaling from urban to a regional level. The applied framework is using a hierarchical system: *general spheres*, *theme* and *indicator*. Due to the thematic congruence of the framework the *general spheres* (Table 2) of resilience - environment, infrastructure, economy, society and governance - were completely adapted to the new regional resilience framework.

The second framework level of *themes* was thoroughly modified in consideration of the planning duties of the county level. Each county has mandatory duties as well as some voluntary duties and duties imposed by the federal government and/or state. The following duties are mandatory (Landeszentrale für politische Bildung (LpB), 0000):

- Waste management
- Health system
- Social and youth welfare services
- Public transport
- Environment and nature conservation
- Forest administration
- Road administration
- Agriculture
- Surveying and mapping
- Commercial inspectorate
- Pension office
- Veterinary

In order to develop meaningful indicators on the county level, these mandatory duties have to be considered, so that the authorities can deduce adaptation measures in their area of legal competence. Later on, the indicators should provide the means to monitor and evaluate implemented measures.

During the process of developing the indicator set (Step 1.3), 17 themes were selected for the regional scale. On this basis, a set of 23 indicators was deduced considering the spatial scale at county level (Table 2). The final themes and indicators are shown in Table 2. It also shows the linkage of the themes to a county's planning duties. Further, the public availability of indicator data was a selection criteria, because the developed index should be low-threshold for the application.

Compared to the urban resilience indicator set of Feldmeyer et al. 2019 some indicators were introduced and removed. In the environmental sphere, the theme of *Agriculture and forest* was additionally introduced. The sphere of infrastructure is subdivided into *Street, Health care (epidemiological & individual citizen), Local supply* and *Public transportation*. Those themes replaced the urban themes (Feldmeyer et al. 2019) of *Settlement structure, Energy* and *Drinking and wastewater*. For the economic sphere, a locally-focused view on *Business* was exchanged with the more general descriptive theme of *Unemployment*. The people-centred theme of *Knowledge and risk competence* was disregarded as well as the municipality focused theme of *Research projects* within the municipality. Similarly, on the governance level *Participation* was dropped.

In Step 1.4. the transformation of the initial indicator set is

Table 2
Regional climate resilience indicators based on literature analysis and administrative responsibilities of counties.

Sphere	Theme	Indicator		Duty	Justification
Environment	Soil and green spaces	en_pe	Degree of ground sealing[1]	Environment and nature conservation	(Yoon et al. 2016)
	Water bodies	en_wa	Proportion of structurally shaped settlement and traffic area in the official flood area[1]	Environment and nature conservation	following (Geis and Kutzmark 1995)
	Biodiversity	en_bi	Share of nature conservation and protection areas[1]	Environment and nature conservation	(US Indian Ocean Tsunami Warning System Program 2007)
	Air	en_ap	Air emission index[4]	Environment and nature conservation	(Riedel et al., 2016; Mitigation Framework Leadership Group, 2016)
	Agriculture and forest	en_ag	Degree of organic farming[4]	Agriculture administration	(Welle et al., 2014; Renschler et al., 2010)
		en_fo	Proportion of undissected forests[1]	Forest administration	(Cutter et al., 2008; Mitigation Framework Leadership Group, 2016)
Infrastructure	Streets	in_sp	Accessibility of large centres[3]	Road administration	(Becker et al. 2015)
	Health care	in_ho	Hospital beds[2]	Health system	(Cutter et al. 2010a)
		in_dp	Nearby doctors[3]	Health system	(Cutter et al. 2010a)
	Local supply	in_lp	Accessibility of supply with daily goods[3]	Road administration	(Renschler et al. 2010)
	Public transport	in_pu	Proximity of public transport[2]	Public transport	(ARUP and Rockefeller Foundation 2014)
Economy	Innovation	ec_re	Employees in research intensive companies[2]	Business development	(ARUP and Rockefeller Foundation 2014)
	Employment	ec_em	Employment[5]	Business development	(Oregon Seismic Safety Policy Advisory Commission 2013)
	Economy	ec_gr	Gross Domestic Product[4]	Business development	(Becker et al. 2015)
Society	Health	so_he	Sick days[6]	Health system	(Becker et al. 2015)
	Sociodemographic	so_ag	Share of citizens ABV6/U65[4]	Social and youth welfare	(Cutter et al. 2010b)
	Civil society	so_vo	Voter turnout[4]	Democracy	(Poland 2008)
	Social security	so_sp	People in need communities[4]	Social and youth welfare	
	Civil protection	so_pp	Nearby police stations[3]	Civil protection	(Becker et al. 2015)
		so_ap	Proximity of hospitals[3]	Civil protection	(ARUP and Rockefeller Foundation 2014)
Governance	Budget	go_dp	Municipal debt[4]	not directly	(Abel Schumann 2016)
		go_in	Municipal income[4]	not directly	(Abel Schumann 2016)
	Administration	go_su	Support of climate protection agreement[4]	Climate protection	following (Mitigation Framework Leadership Group 2016)

Data sources: [1](IOER 2019) [2](BBSR 2019)[3] (BMEL 2019) [4] (statistik-bw, 2019) [5] (BA 2019) [6] (BKK 2019).

performed, as the indicators are measured in different measurement scales. For using them in calculations such as aggregations, they need to be transformed.

For the transformation of data, the normalization method was chosen. Several normalization methods exist from which the min–max normalization is selected as depicted in equation (Joint Research Centre-European Commission (JRC), 2008). This normalization results in values from zero to one and shifts the distribution. Important to note is that the distribution of the data itself is not changed.

Equation 1: min–max transformation

$$z = \frac{X_{ij} - X_{(\min)}}{X_{(\max)} - X_{(\min)}}$$

2.2. Validation of initial indicators

The amount of literature concerning resilience has exponentially grown over the last decade. Resilience indices are developed for different hazards, scales and definitions of resilience. The vast majority is based on thorough theoretical deduction, but only a few attempts for empirical validation or verification exist (Burton, 2015; Bakkensen et al., 2017). Therefore, although the indicators are theoretically sound, they are not tested if they measure climate resilience in reality.

Indices are used to measure complex phenomena where no single indicator captures all aspects of the indicandum (phenomenon of interest). Hence, starting with the objective of the index stating the indicandum is appropriate (Bastianoni et al. 2012). In order to validate indicators and indices empirically the choice of an outcome to validate against is essential, although the selected outcome can only be a helpful tool to assess for a better understanding. In case of dealing with a multidimensional indicandum, such as resilience, no single outcome exists and different outcomes need to be considered. For example, Bakkensen et al. (2017) selected property damages, fatalities and frequency of disaster declaration as outcomes for the validation of disaster resilience and vulnerability indices. They further stated that resilience and vulnerability are limited to those three outcomes. Burton (2015) used images to measure the recovery process after Hurricane Katrina to validate resilience indicators of communities empirically. This example states, indicators of the same indicandum – in this case disaster resilience – can be validated against different outcomes, which contributes to a broader understanding of the indicandum.

Applied to the context of indicandum climate resilience, life expectancy seems to be able to cover a wide range of the aims of the indicandum. Life expectancy is the number of years a newborn can hope to live, based on the latest mortality table calculations of the federal state of Baden-Württemberg. In order to live a long and healthy life, essential factors are healthcare, health, wealth, education and development (Otoiu et al. 2014). Since climate change projections predict an increasing frequency and magnitude of climate-induced hazards, extreme event related outcomes should be considered. Consequently, insurance data about damages due to floods and storm, reported over a period of 15 years (GDV 2018), are selected as the second and third outcome. The damage data of the insurance companies in Baden-Württemberg have excellent spatial coverage of 95% of all buildings due to the historically compulsory insurance until 1993 (GDV 2018).

In order to validate the indicators, the preliminary analysis shows that non-linearity and violation of the normal distribution (histogram, Kolmogorv-Smirnov-Test) assumption have to be considered. Therefore, a random forest model implemented in the RandomForest Package as a non-linear method is selected (Step 2.1) (Liaw and Wiener, 2002). Three models are calculated, one with each of the three defined outcomes as a prediction. The evaluation criterion was the contribution to reducing the test error. Indicators not decreasing the test error in at least one of the three models (storm, flood, life expectancy) were consequently removed from the index (Table 3).

Table 3
Empirical validation of county resilience indicators.

Code	Indicator	Storm	Flood	Life expectancy
en_pe	Degree of ground sealing	No	Yes	Yes
en_wa	Proportion of structurally shaped settlement and traffic area in the official flood area	No	No	No
en_bi	Share of nature conservation and protection areas	Yes	Yes	No
en_ap	Air emission index	No	Yes	Yes
en_ag	Degree of organic farming	Yes	Yes	Yes
en_fo	Proportion of undissected forests	No	No	No
in_sp	Accessibility of large centres	Yes	Yes	Yes
in_ho	Hospital beds	No	Yes	No
in_dp	Nearby doctors	Yes	Yes	Yes
in_lp	Accessibility of supply with daily goods	Yes	Yes	Yes
in_pu	Proximity of public transport	Yes	No	No
ec_re	Employees in research-intensive companies	No	No	No
ec_em	Employment	No	No	Yes
ec_gr	Gross Domestic Product	Yes	No	No
so_he	Sick days	Yes	No	Yes
so_ag	Share of citizens ABV6/U65	Yes	Yes	No
so_vo	Voter turnout	Yes	No	Yes
so_sp	People in need communities	Yes	No	Yes
so_pp	Nearby police stations	No	No	Yes
so_ap	Proximity of hospitals	No	Yes	No
go_dp	Municipal debts	No	No	No
go_in	Municipal income	No	No	No
go_su	Support of climate protection agreement	No	No	Yes

2.3. Aggregation of the index

The aggregation of indicators to a composite index requires two main steps, which both crucially influence the final index (Becker et al. 2017). The aggregation method can be done by different mathematical means. All mathematical calculations are done with R (Team 2019) within R Studio (Team, RStudio, 2016).

To build a composite index, it is important to define indicator weights. There are two main methodological approaches which can be used to build a composite index:

1. The first approach can be described as topic-driven, where weights are developed by experts, surveys or according to thematic groups and are then chosen *equally or hierarchically*. Equal or hierarchical weights are easier to communicate to stakeholders which are especially important in the science-policy interface. Moreover, transferability and transparency are increased, and the weights appear logically justified (Birkmann and Welle, 2016; Cutter et al., 2010b; Rød et al., 2012).
2. The second approach proposes purely data-driven, statistical weights for the indicators. However, as Becker et al. (2017) argue, different variances as well as possible correlations distort the selected weights and result in an undesired impact. Although, even correlated indicators can measure different phenomena and do not necessarily duplicate, hence overstating the same phenomena which cannot be discerned adequately by purely data-driven approaches.

Against this background and acknowledging the logic and correctness of both sides, the present paper implements both approaches and validates them using empirical data to justify the aggregation method. Within these two approaches, four methods were identified and used (Table 1). The implementation of the methods allows to assess the impact of the aggregation method on the index. This contributes to the transparency, robustness and sensitivity assessment of the index. The first method (Step 3.1.a.) explores and understands the data as well as its characteristics when constructing the index with equal weights (eqw).

1. The second method (Step 3.1.b.) implements the mixed equal hierarchical expert weights approach (hw). Within climate resilience, two hierarchical levels are developed. On the first level, five main dimensions are equally weighted. The number of themes within each dimension varies but is covered by a single indicator. Consequently, each theme is represented by a single indicator. Hence, equal weights are assigned within each dimension to each theme resulting in different weights for indicators on an index level. For example, environment has the weight one fifth due to five dimensions. Within the theme environment, air also has one fifth due to five themes within the environment.
2. The third method (Step 3.1.c) is the Wroclaw Taxonomic Method (wroclaw). This method is widely applied for the development of social, as well as economic, indicators (Schifini, 1982; Quirino, 1990; Muro et al., 2011; Cwiakala-Malys, 2009). The method selects one indicator as the benchmark, which comes closest to an ideal unit. For the other indicators thereafter, the Euclidian distances to this benchmark indicator are calculated and ordered in respect of the proportion of the distance to the optimal situation (Vidoli and Fusco, 2018).
3. The fourth method (Step 3.1.d) is the Mazziotta-Pareto-Index method (mpi). This method measures two aspects: the mean level and the unbalance of each indicator. The method is based on a linear aggregation but a penalty in case of unbalance corrects for this unbalance (Muro et al. 2011).

2.4. Calculation of robustness and sensitivity

In Step 4.1. the intra-methodological influence is assessed, which contributes to the overall need of a composite index to be transparent, robust and traceable (Welle and Birkmann 2015). Cronbach's Alpha (Step 4.1.a) and Guttman's Lambda (Step 4.1.b) are commonly used tests to describe reliability. These tests assess the homogeneity of items for constructing an index. Considering regional climate resilience, reliability explains the internal consistency of the indicators to the indicandum. According to the JRC (2008), Cronbach́s Alpha within the range 0.6 to 0.8 is desirable. Guttmańs Lambda calculates six lambdas in succession, where Lambda 3 is equal to Cronbach́s Alpha. Guttmańs Lambda presents lower bounds of reliability.

In Step 4.2.a. a global sensitivity analysis (GSA) is applied to all four indices calculated in Step 3.1.a – 3.1.d. The sensitivity analysis adds and quantifies the uncertainty of the composite index, to the knowledge of the internal consistency of the items (Saltelli 2002). For conducting the GSA the free open source tgp package (Gramacy 2007) is applied. In a GSA, all input items are changed at the same time. In contrast, the local sensitivity analysis changes one item at a time. The sensitivity function of the tgp package is an implementation of a Bayesian approach. Normally distributed Gaussian noise is added to the function of each item. The Bayesian approach significantly reduces the computational effort and still produces reliable results (Oakley and O'Hagan 2004).

2.5. Validation of indices

In Step 5.1.a. an empirical validation of the aggregation methods is conducted. As already stated in Chapter 2.2, validation is crucial at all stages of the index creation. Therefore, a double validation is performed in this paper. Firstly for the individual indicators (Step 2.1.a) and secondly for the aggregation method (Step 5.1). Hence, a nonlinear and nonparametric correlation was performed for each index in order to assess the impact of the different aggregation method.

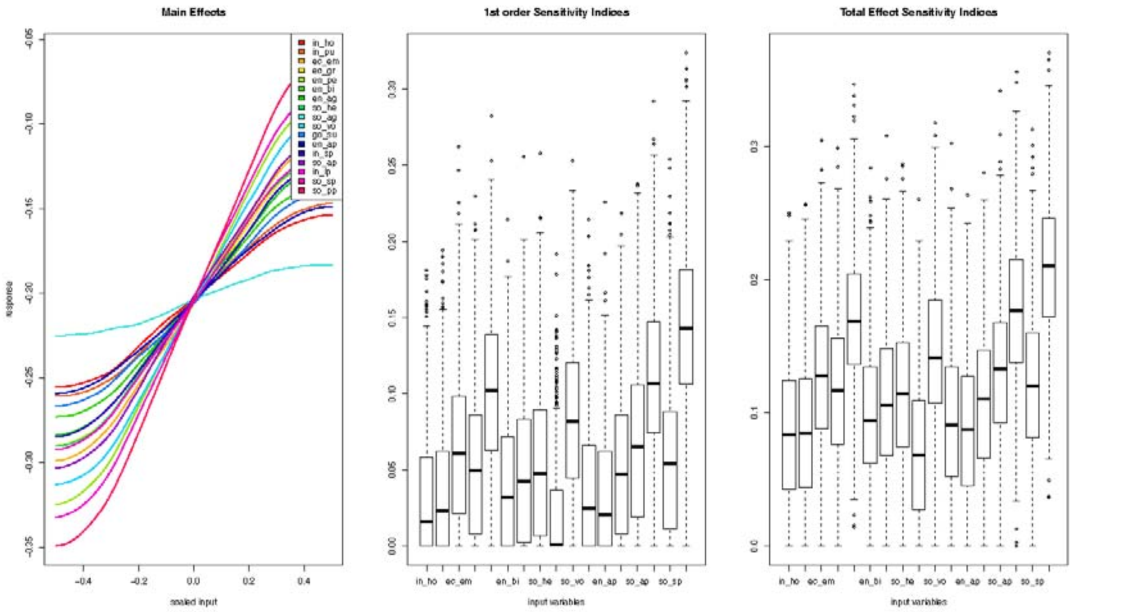

Fig. 2. Display of the global sensitivity analysis of the resilience index based on the Wroclaw approach.

2.6. Application of the final index to the spatial scale

Finally, the validated indicators and the most adequate aggregation method are selected, and the index is implemented for the federal state of Baden-Württemberg. With the resulting climate resilience index for the state, including a county resolution, the index is initially analysed with regards to indicators which may explain high or low resilience. Furthermore, rural and metropolitan counties are compared (see Fig. 1). For both comparisons, boxplots are plotted. The mean value comparison was conducted with the non-parametric Wilcoxon-Test.

3. Results

The results follow the stated objectives and each section builds on the previous but also includes stand-alone results. First, the selection of indicators and reducing them based on statistical tests. Second, the building of the composite index within the sensitivity analysis and second stage validation. Third, the analysis results of regional climate resilience based on the index developed in the previous two sections.

3.1. Regional climate resilience indicators (Step 1 – 2)

The proposed indicators are based on literature, administrative responsibilities and the framework for climate resilience (Table 2). They are tested regarding their suitability for a composite index and by their contribution in explaining one of the three outcomes (storm, flood, life expectancy).

Preliminary analysis steps are indicating a violation of the assumption of normality as well as linearity. Therefore, correlation analysis is based on a pairwise nonparametric and nonlinear analysis. High correlation ($R > 0.70$) reveals the three pairwise combinations of the indicators: *Accessibility of supply with daily goods, Nearby doctors* and *Nearby police stations.* All three are covering important aspects of climate resilience but stating a similar problem of the supply of services in rural areas compared to metropolitan areas, thus summarizing the question of accessibility. Based on this analysis, the indicator *Nearby doctors* was removed as not only the accessibility but also the "per capita" number is important while the medical capacity in emergencies is additionally covered by *Hospital beds.* The other two indicators were kept although they are highly correlated because they cover different aspects in different spheres of the framework.

Degree of ground sealing was highly negatively correlated with *Accessibility of large centres, Nearby doctors, Accessibility of supply with daily goods, Proximity of hospitals* and *Nearby police stations.* The negative correlations here are somehow expected and revealing conflicting goals within climate resilience. Hence iťs not incoherence of the framework but rather strength in incorporate both perspectives. The necessity of both aspects requires the inclusion of both sides.

In order to the supervised machine learning approach is considering all resilience indicators as input and storm, flood or life expectancy as output (Table 3). Within Table 3, *Yes* states that the indicator contributes to reducing the test error, and *No* declares indicators are irrelevant in the model. The five most important indicators regarding the output life expectancy were *Voter turnout, Degree of organic farming, Nearby police stations, Sick days* and *Accessibility of supply with daily goods.*

For the damage related to the storm, the five most important indicators were *Degree of organic farming, Share of citizens ABV6/65, Gross Domestic Product, Employment, Sick days,* and *Voter turnout.* The five most important indicators regarding the prediction of flood damage were: *Share of citizens ABV6/U65, Accessibility of large centres, Accessibility of supply with daily goods, Hospital beds, and Air emission index.* In all three models, five indicators did not contribute to reducing the test errors on the test data: *Proportion of structurally shaped settlement and traffic area in the official flood area, Proportion of undissected forest, Municipal debts, Municipal income and Employees in research-intensive companies* (Table 3). These five indicators were consequently removed from the further construction of the index.

3.2. Regional climate resilience index (Step 3–5)

After determining the reliability of the validated and reduced set of indicators (Step 2), the four aggregation methods are calculated (Step 3). Subsequently, based on the sensitivity analysis in conjunction with the correlation analysis against the outcomes (Step 4), one final index is selected (Step 5).

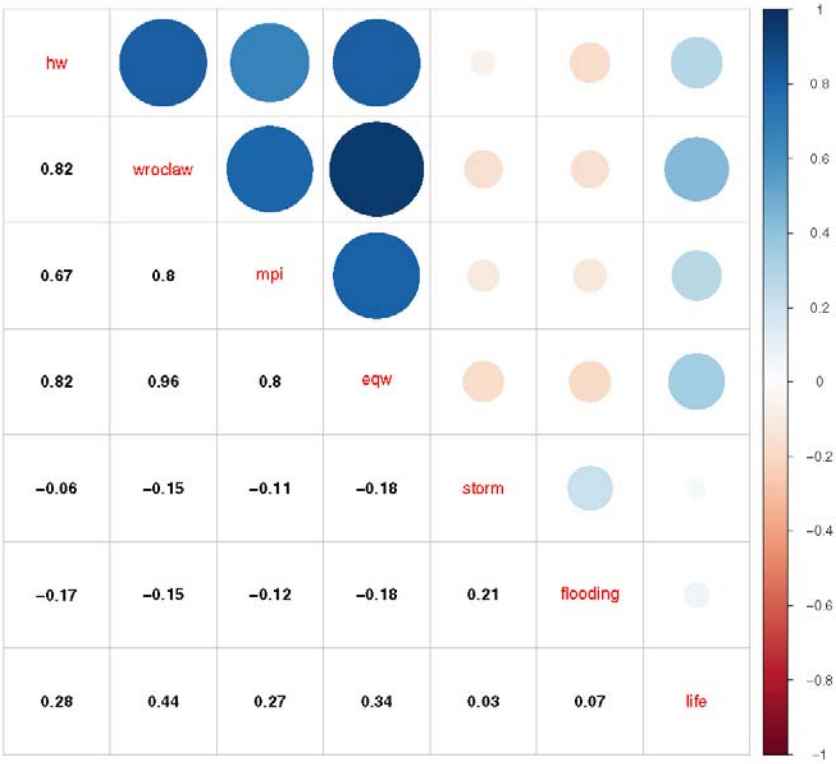

Fig. 3. Correlation plot of the four aggregation methods and three outcomes.

The reliability (Step 4.1.a + 4.1.b.) of the indicator set is with a Cronbach's Alpha of 0.84, the lower boundary of the 95% confidence interval of 0.78 and the upper boundary of 0.91, well within recommended values (Revelle and Revelle 2015). Cronbach́s Alpha is the most frequently used measure. Still, it tends to underrate the reliability and overrate the first factor saturation. The Guttmańs Lambda for the indicator set is 0.95. Summarizing the set has strong reliability and is suitable for constructing an index.

For all four indices, the global sensitivity analysis was conducted (Step 4.2.a). The result of the Wroclaw aggregation method is shown in Fig. 2. Based on the comparison, the Wroclaw method is best suited to aggregate the set of indicators. Within the other methods (hw, mpi, eqw), the first order, as well as total effect, was unequally distributed amongst the indicators.

Fig. 3 displays the correlation matrix for the indices with the outcome validators. Overall, resilience indices are positively correlated. All indices are also, as expected, positively correlated with life expectancy and negatively correlated with the damages associated with floods and storms. The highest correlation for life expectancy showed the Wroclaw-Index with 0.44, which also correlated negatively with the storm and flood damages. The negative correlation to damages is only slightly better covered by the Equal-Weight-Index. Therefore, consistent with the sensitivity analysis, the Wroclaw-Index performs best. Consequently, the resilience indicators aggregated with Wroclaw Taxonomic are validated as the best Regional-Climate-Resilience-Index (RCRI), which is used for further calculations.

3.3. *Regional climate resilience implemented on county level (Step 6)*

The newly created and validated RCRI is applied to the case study region of Baden-Württemberg. For explaining the spatial attributes in detail, the dataset is split into the most and least resilient counties (Fig. 4) as well as into rural and metropolitan areas (Fig. 5). Furthermore, the county climate resilience is presented in a spatial map (see Fig. 5).

In Fig. 4, the ten most resilient counties were grouped into one group and the ten least resilient counties into a second group. As anticipated, the life expectancy of the top group is significantly higher and the damages caused by storm and flood lower, although not statistically significant. The lower group has higher values in the environmental sphere (e.g., *Degree of ground sealing (en_pe)* or *Share of nature conservation and protection (en_bi)*. Statistically significant indicators in favour of the top group are *GDP (ec_gr), Degree of ground sealing (en_pe), Voter turnout (so_vo), Support of climate protection agreement (go_su), Air emission index (en_ap), Accessibility of large centres (in_sp), Proximity of hospitals (so_ap), Nearby doctors (in_dp), Accessibility of supply with daily goods (in_lp)* and *Nearby police stations (so_pp)*. Eight indicators are not significantly different.

Fig. 5 demonstrates the comparison of the seven metropolitan counties with seven rural counties. These counties are classified as city and rural by the Statistical Office of Baden-Württemberg (statistik-bw, 2019). The results of the aggregated Wroclaw Index suggest that the metropolitan counties are (statistically) significantly more resilient than the rural counties, which is consistent with lower damages although not statistically significant. Life expectancy, in contrast, is slightly higher by means of the mean but also has a greater variance. The rural counties have higher resilience concerning *Employment (ec_em), Degree of ground sealing (en_pe), Share of organic farming (en_ag),* and *people in need communities (so_sp)*. Reciprocal metropolitan areas have a higher *GDP (ec_gr), Accessibility of supply with daily goods (in_lp), Proximity of hospitals (so_ap), Nearby doctors (in_dp)* and *Nearby police stations (so_pp)*.

The map (Fig. 6) shows that the metropolitan regions (Stuttgart, Freiburg im Breisgau, Baden-Baden, Mannheim) tend to have a higher resilience compared to the more rural areas. The obvious exception

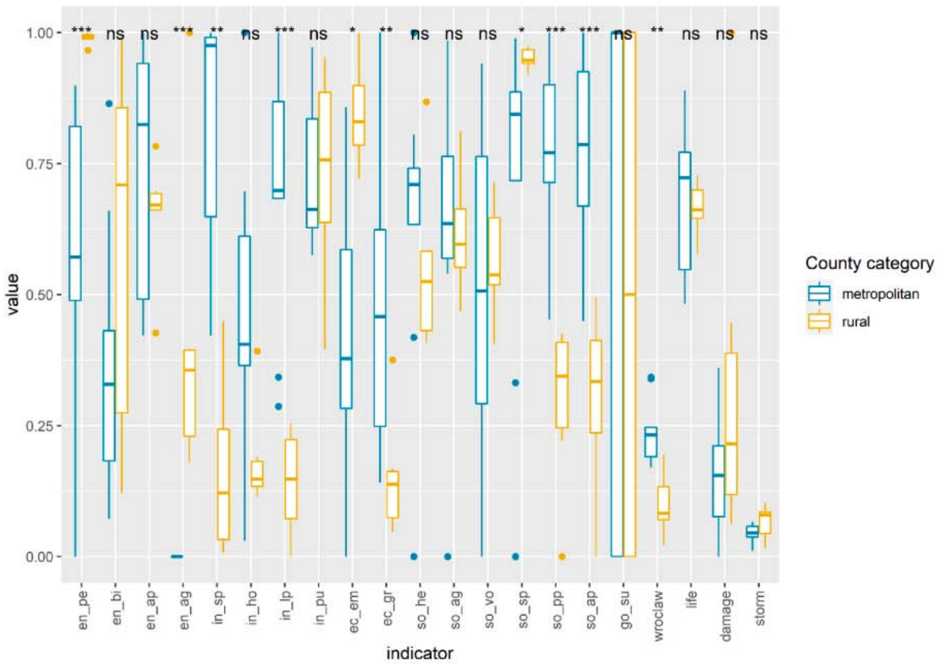

Fig. 4. Boxplots and statistical test of mean between high and low resilient counties (ns: p > 0.05; *: p < = 0.05; **: p < = 0.01; *** : p < = 0.001 ****: p < = 0.0001).

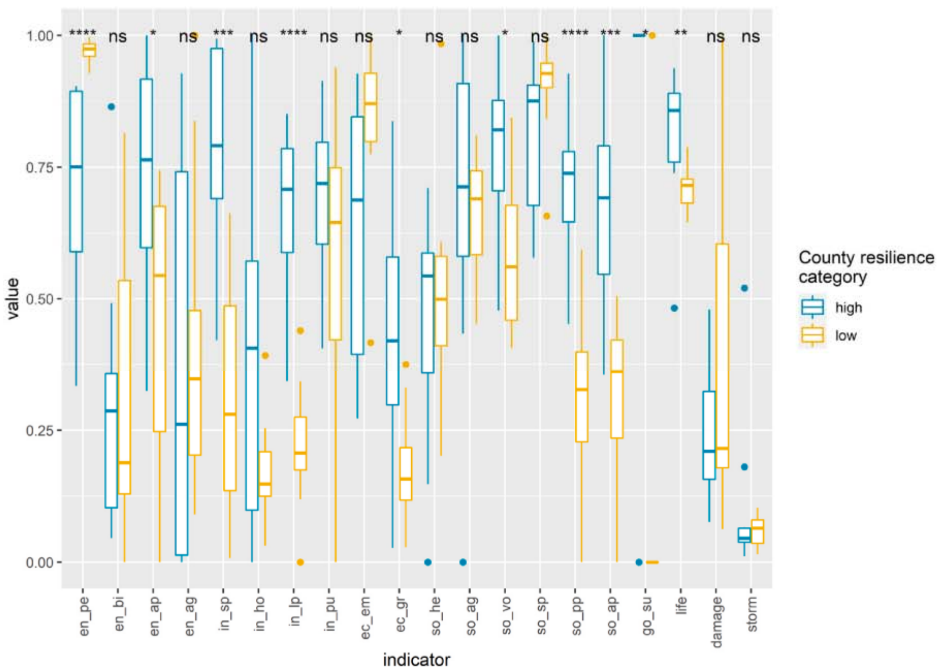

Fig. 5. Boxplots and statistical test of mean between rural and metropolitan counties (ns: p > 0.05; *: p < = 0.05; **: p < = 0.01; *** : p < = 0.001 ****: p < = 0.0001).

within this pattern is Pforzheim, which is a metropolitan area but with only low resilience. A deep structural transformation effects the city of Pforzheim due to the decline of the jewellery industry. The rural county of Rottweil, on the other hand, is located in the black forest and is highly resilient despite its rurality.

4. Discussion

The accomplished methodological approach and the results are giving interesting insights regarding the importance of indicator selection, indicator validation, aggregation, validation of index

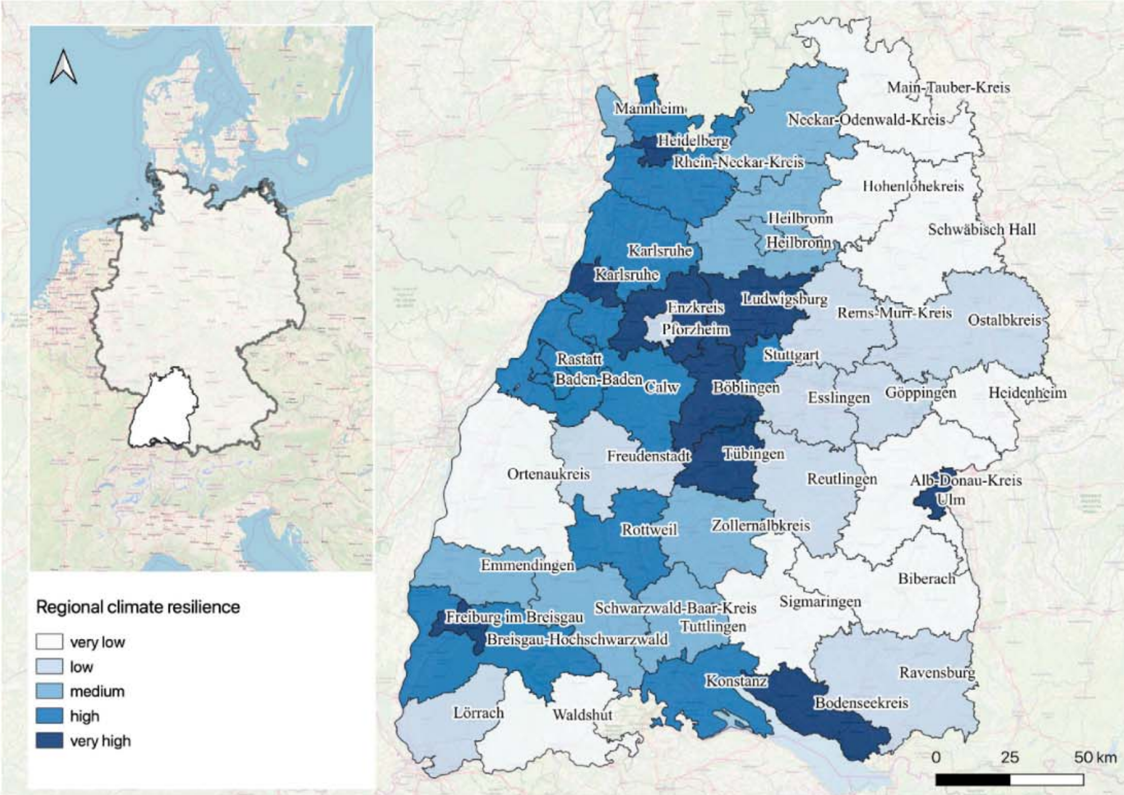

Fig. 6. Map of the regional climate resilience index in Baden-Württemberg (resilience classes are based on quantiles).

aggregation methods and the spatial scale which will be examined in the following chapter. Also, the limits of this approach, for example, lack of data or completeness of the indicator set, need to be discussed.

4.1. General

The selection of the indicators proved to be equally important as the selection of the aggregation method. Moreover, the only theory-based approach established on the climate resilience framework and indicators based on literature did not perform as predicted by the theory which is in line with the results of Bakkensen et al. (2017). The application of the global sensitivity analysis (Step 4.2.a) proved to be very useful. Comparing the four aggregation methods (Step 3), the Wroclaw-Index (Step 3.1.c.) achieved the best results. The Wroclaw-Index is able to balance the impact and direction of all indicators equally. Subsequently, the correlation (Step 5.1.a.) with the outcomes was also in favour of the Wroclaw-Index approach. The moderate values of the correlation coefficient are due to the fact that the index is designed for a stressor-independent assessment of resilience and not specifically for life expectancy, nor flood damage or storm damage. In comparison, the empirical model and resilience index designed by Burton (2015) achieved low to moderately low model explanatory power. Designed independently of the stressor, the new regional climate resilience index still performed as expected and displayed the stressor-independent resilience of regions. Moreover, the part of climate resilience which was not exposed by the index might be explained by contextual factors such as social networks, feeling of belonging, trust in authorities, knowledge, risk perception - which are quantitatively based on secondary data hard to measure but are also part of climate resilience.

4.2. Indicators

Five indicators were removed during the first stage of empirical validation on the indicator level (Step 2.1.a). In the case of water and forest, the included indicators were only second choice. For forest and water, the status of the water bodies and respectively the status of the forest were to be included as indicators. This data based on measures of the status exist but are only published via a WMS service. Hence, it was not possible to aggregate them on the county level to a meaningful indicator. The respective authorities did not want to share the data upon request. As a result, the included indicators were substituted based on available data, but this approach did not allow to capture the themes of water bodies or forests, respectively. The empirical validation revealed that a lack of accessible data in this regard. Thus, such validations suggest a clear need for open data in order to monitor and evaluate interdisciplinary phenomena and climate resilience. Regarding municipal income and debt, two lines of argumentation appear. Firstly, financial ability does not result in any dedicated action by the corresponding communities at the moment. It can be seen as a necessary, but not imperative condition and other factors overrule it. Secondly, the municipal budget is not on the same administrative level as the other indicators. Although the county resilience is based on the municipalities, the county budget would have been a better and more appropriate spatial and administrative scale. The fifth indicator removed, *Employees in research-intensive companies* might have been related to the selected outcomes. The contribution regarding climate resilience is an important aspect for a future resilient economy and the ability to adapt and evolve, which might not have been covered sufficiently within the outcomes.

4.3. Assessment of climate resilience

The assessment of resilience is not seen as a substitute for detailed hazard, vulnerability and risk assessment. On the municipal or site level, a detailed multi-hazard assessment (including sudden and slow-onset) and vulnerability assessment on a high spatial resolution may need to be conducted within a multi-criteria assessment framework (Ravankhah et al. 2019). The resilience assessment could be seen within a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis as the strength, vulnerability as the weakness analysis and the hazard assessment looking into the threats. Understanding all parts of the SWOT analysis is indispensable for effective strategic planning.

In explaining the three empirical outcomes (storm, flood, life expectancy), four out of five spheres proved to be relevant: Environment (*Degree of organic farming, Air emission index),* Infrastructure (*Accessibility of large centres, Accessibility of supply with daily goods)*, Economic (*GDP, Employment),* Social (*Share of citizens ABV6/U65, Sick days, Voter turnout, Nearby police stations)*. Governance (*Support of climate protection agreement)* is not amongst the top five determinants but statistically significant regarding climate resilience (Fig. 5). Thus, all five spheres are essential and underline the socio-economic a socio-ecological character of climate resilience.

By taking a closer look at the five most important indicators regarding the outcome of life expectancy, the most important variable is *voter turnout*. Non-voting attitude is strongly dependent on the social class, and statistically, non-voters have lower incomes and lower education (Güllner, 2013) which are important aspects of resilience in line with literature. *Degree of organic farming* is also a predictor of life expectancy. This might be due to a general higher awareness of organic food, resulting in healthier nutrition. Organic farming also results in a healthier environment, e.g. because of reduced input of pesticides and therefore with a positive impact on health. *Sick days* are an obvious determinant of life expectancy. *Nearby police stations* and *Accessibility of daily goods* can be summarized as the provision of security and other services.

4.4. Climate resilience and empirical validation

The empirical validation with damages from storm and flooding events reveals two difficulties regarding the applied definition of climate resilience. Firstly, compared to other resilience approaches, e.g. flooding resilience (Qasim et al., 2016; Shah et al., 2018), the used definition is not specific to one particular threat. Consequently, this approach stresses the importance of increasing the general climate resilience due to the high uncertainty of further extreme events and climate change. This underlying concept results in a lower extreme event specificity of the index, which is reflected in a lower correlation to storm and flood. Hence, it reflects the trade-off between extreme event-specific resilience vs general climate resilience and inclusiveness. Secondly, because of the pronounced context-specific of climate resilience, interpreting the machine learning results of nonlinear problems, where monodirectional effects exist, is challenging. Though, this finding highlights the complexity and multidimensionality of social systems and the phenomenon of climate resilience and offers insights to multifaceted effect directions.

Opportunities for future research are indicators to measure disaster resilience in Baden-Württemberg but also outcome indicators for empirical validation. For example, the voluntary fire brigade is one of the pillars of civil protection, but a number of manpower available at the state level does not exist, although increasing pressure and deployments regarding natural hazards are reported. The number of indicators within this study was relatively limited and the selection based on theory but still to some degree subjective. Further empirical analysis into more indicators can contribute to the understanding of climate resilience. In addition, the combination of machine learning and, e.g. twitter data, phone records or open street map for developing indicators to measure soft attributes of resilience (such as the feeling of belonging or social networks) opens huge opportunities regarding the measurement of resilience. Lastly, heat stress and wildfires - both projected to increase in frequency and magnitude - could not be considered within this study.

4.5. Climate resilience and spatial scale

The comparison of rural vs metropolitan areas pointed out a significantly higher resilience of metropolitan areas within Baden-Württemberg (Fig. 5). The rural areas have higher environmental resilience and higher employment, which were overbalanced by the other spheres. The high employment level of rural areas is one particular feature of Baden-Württemberg with hidden champions in those areas and in general a very low unemployment rate. The indicator *sick days (so_he)* needs to be examined because a higher rate of sick days might not be entirely negative. It could also be a sign of health awareness as the balance of working culture and self-awareness can be different between urban and rural regions. The provision of goods, services and connectivity of rural areas - as general themes of the rural development debate - is also reflected within the regional climate resilience. Urban areas are offering benefits in their infrastructure.

In light of this analysis, the recommendation for action regarding the improvement of the infrastructure in rural areas gets more critical. In addition, it becomes apparent that urban areas in Baden-Württemberg need to enhance their environmental resilience and parts of social resilience to boost their overall resilience. Nevertheless, both rural and urban areas need to address all aspects of resilience in balance.

5. Conclusion

Only a small number of approaches for empirical validation of resilience indicators are existing, and machine learning approaches are very less used. The study demonstrates the necessity of carefully evaluating every single step in constructing a composite index. Moreover, a thorough theoretical framework for climate resilience in conjunction with literature-based indicators does not necessarily capture the phenomenon. Empirical validation is indispensable but challenging due to the future outcome of climate resilience and lack of empirical data. Especially at the stage of indicator selection and at the stage of choosing the aggregation method, machine learning can be effectively used to reduce bias and improve the index. It was found that different outcomes are essential, where life expectancy was found to be a good approximation in combination with damages from natural hazards. Fostering climate resilience is essential to tackle foreseen and unforeseen challenges which require measurements and the development of composite indicators due to the complex phenomena.

The empirical validation essentially contributes to the performance of the index by giving evidence in selecting the indicators and method. The theory-based expected outcome does not have to coincide with the empirical reality. Global sensitivity analysis further helps in understanding the model and adds to the empirical validation. Life expectancy was found to be a good outcome due to its inclusion of many aspects of resilience, in combination with natural hazards. All five spheres - environment, infrastructure, economy, governance and society - are empirically important for climate resilience. The environmentally better situation of the rural areas does not compensate for the lack of the other spheres and results in an overall lower climate resilience compared to metropolitan areas.

CRediT authorship contribution statement

Daniel Feldmeyer: Conceptualization, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Daniela Wilden:** Methodology, Writing - original draft, Writing - review &

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Appendix D: Measuring knowledge and action changes in light of urban climate resilience (3rd Contribution)

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

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A R T I C L E I N F O

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A B S T R A C T

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.

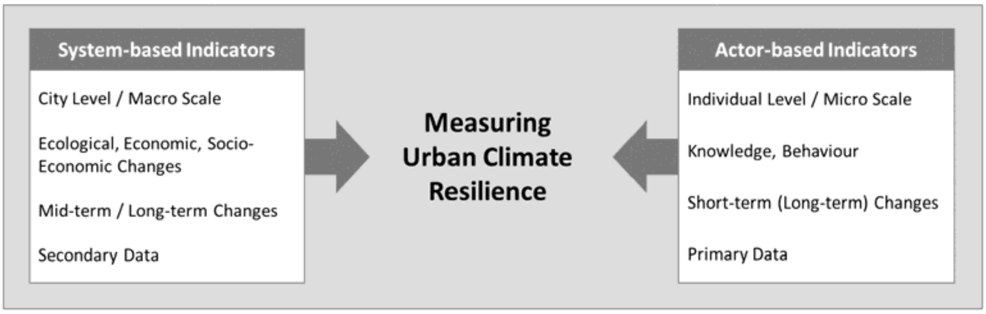

Fig. 1. Monitoring and evaluation framework for climate change adaptation measurements in the context of urban resilience.

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.

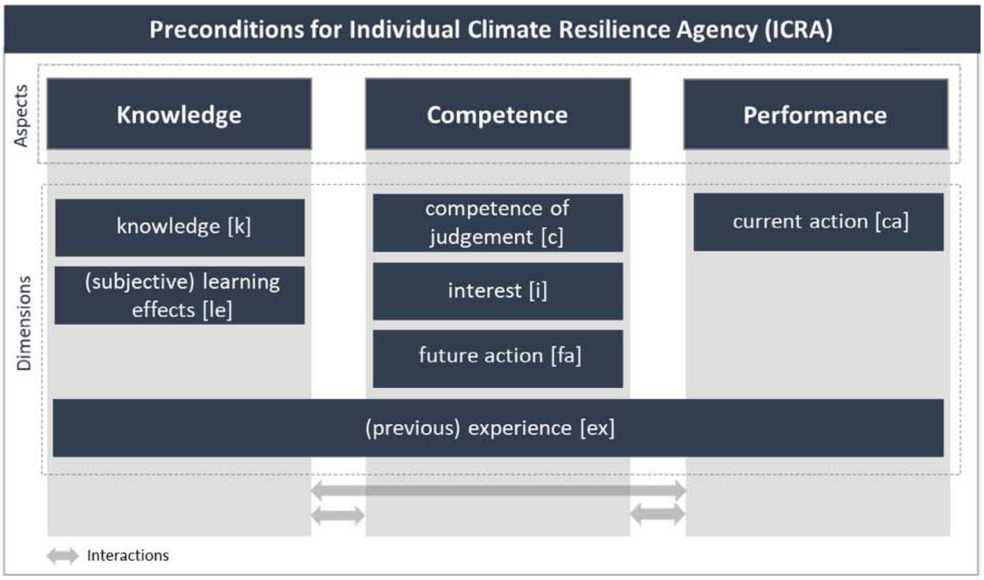

Fig. 2. Deconstructed preconditions for individual climate resilience agency (ICRA).

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

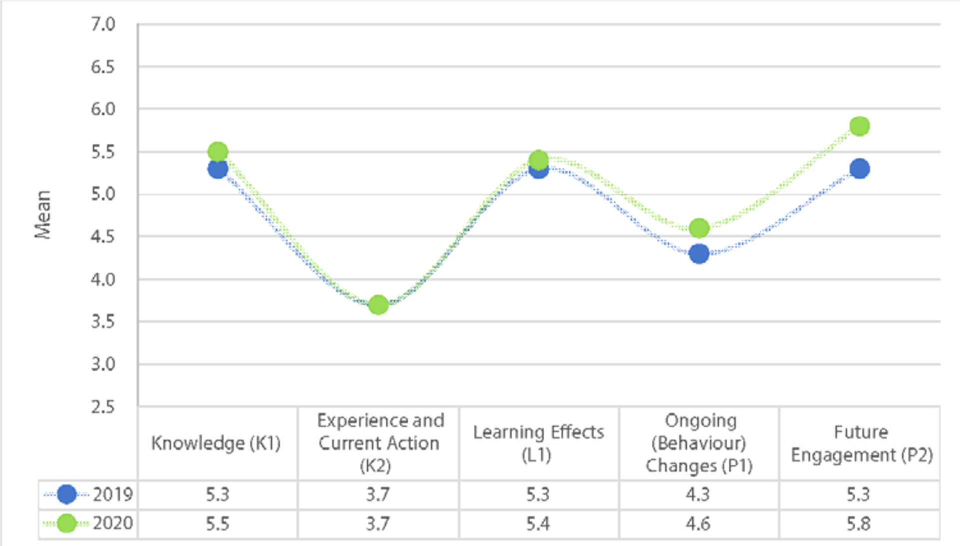

Fig. 3. Means of the composite indicators of 2019 and 2020.

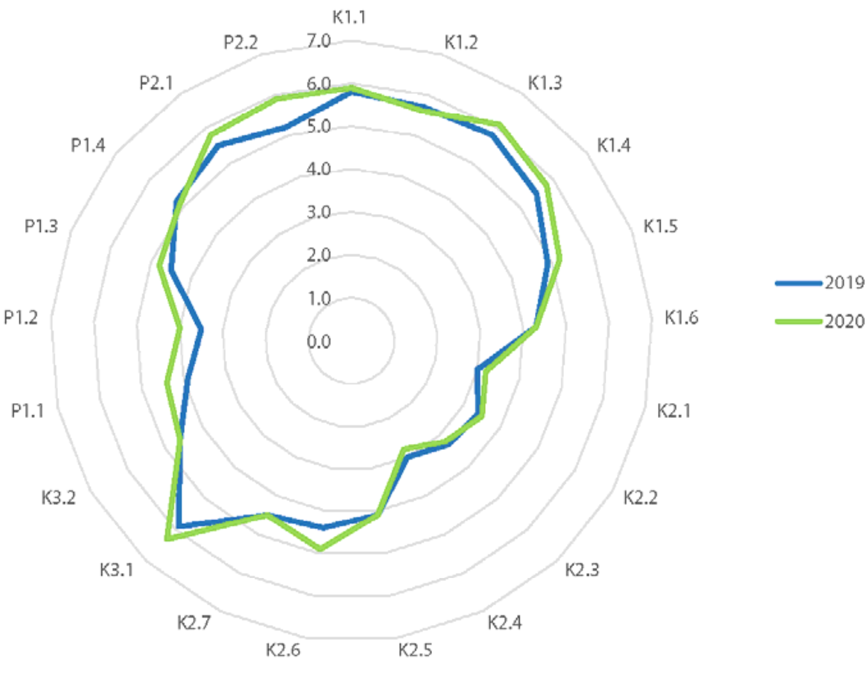

Fig. 4. Individual indicator means of Individual climate resilience agency of 2019 and 2020.

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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Appendix E: Original Repetitive Online Survey – Version 2019

Digital Appendix

Appendix F: Original Repetitive Online Survey – Version 2020

Digital Appendix

Declaration on honour

I declare: I have written this dissertation independently and without unauthorised assistance and only with the help that I have indicated in the dissertation. All text passages that have been taken verbatim or in spirit from published writings, and all information that is based on oral information, are marked as such. I agree to a possible check of my dissertation by an anti-plagiarism software. In the research I have carried out and mentioned in the thesis, I have complied with the principles of good scientific practice as laid down in the "Statutes of Justus Liebig University Giessen to Ensure Good Scientific Practice".

Giessen, 15.03.2022

Place, Date

Signature