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Review Article

Towards a web tool for assessing the impact of climate change adaptation measures on heat stress at urban site level

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Abstract

In view of the increased frequency of heat events and their negative effects, principally in cities, many scholars and practitioners are focusing on ways of adapting to climate change. The urban population and, especially, vulnerable groups, are now being affected to such a degree that adaptation measures are deemed necessary. Clearly, the planning and implementation of such measures are dependent on municipal resources. Tools can greatly assist in the planning of such measures at urban site level. This article provides a systematic review of the tools currently available for planning and implementing climate change adaptation measures in cities. The results offer a comprehensive overview of existing planning tools, which can also serve as a handy look-up document for urban planners searching for such tools. We find that many of these tools require considerable improvement and optimisation. For example, our findings demonstrate that outputs may be overly generalised, often there is no way of entering site-specific information while additional co-benefits (e.g. ecosystem services) are ignored. By analysing selected tools, we pinpoint and discuss requirements for future planning tools. In particular, we present a concept for a tool currently under development which is designed to assist in the planning and implementation of heat adaptation measures at diverse (small) spatial scales. The advantages of this tool are that it can assess the indoor thermal situation in addition to outdoor conditions, thereby providing comprehensive information on the suitability of adaptation measures. Furthermore, decision-making processes could benefit from some estimation of the likely co-benefits (here, ecosystem services) if proposed adaptation measures were implemented.

Keywords

tool, climate change adaptation measures, urban heat stress, site level, model areas, urban planning

Introduction

The recently published IPCC Sixth Assessment Report highlighted once again the increasing pressures that cities are facing due to global climate change. With very high confidence, the panel states that "cities intensify human-induced warming locally, and further urbanization together with more frequent hot extremes will increase the severity of heatwaves" (IPCC (Intergovernmental Panel on Climate Change) 2021, p. 33). The ongoing process of urbanisation is clearly having an adverse impact on the state of natural ecosystems. In particular, green spaces are being sealed or their condition seriously degraded under the extreme climatic conditions in urban areas. This is also affecting the provision of ecosystem services (ES) and, thus, the quality of life and health of the urban population (Maes et al. 2014).

Increasing urbanisation also leads to increased thermal stress on residents. Heat stress is one of the most significant repercussions of climate change on the well-being and health of city residents (Kovats and Hajat 2008, UBA (Umweltbundesamt) 2012, Erens et al. 2021). The result is higher heat storage and higher maximum temperatures in cities compared to the surrounding countryside – the so-called urban heat island effect (Oke 1973). Heat stress can be seen in the limited physical and mental performance of humans, as well as the growing morbidity and mortality, especially related to the growing stress of the cardio-vascular system and metabolic disorders leading to an increasing hospitalisation rate (Jendritzky 2007, VDI (Verein Deutscher Ingenieure) 2008, UBA (Umweltbundesamt) 2009, UBA (Umweltbundesamt) 2015, Karlsson and Ziebarth 2018, UBA (Umweltbundesamt) 2020). Sleep disturbances are also considered to be a result of heat stress due to the lack of cooling effect within cities during night-time (Forsa-study (Gesellschaft für Sozialforschung und statistische Analysen mbH) 2010).

Clearly, adaptation measures are required to ensure the preservation and protection of urban ecosystems and a good quality of life for local residents. Adaptation to climate change has been defined as the "process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects" (IPCC (Intergovernmental Panel on Climate Change) 2014, p. 5). It was also one of the most important topics of negotiation at the 26th Conference of the Parties held in Glasgow in 2021, which underlined the need to strengthen adaptation measures and called upon the Parties to integrate adaptation more strongly into local, national and regional planning (COP 26 (Conference of the Parties 26) 2021). It is only by adapting to the changing climate that cities can remain livable spaces for people and nature in the years to come. For this purpose, there already exists a wide range of adaptation measures from technical solutions, such as the installation of outdoor blinds to avoid excess interior heat (Kuhn et al. 2001, Fosas et al. 2018, Schünemann et al. 2021b), to natural solutions, such as planting street trees to provide extra shade (Westermann et al. 2021). Extensive areas of urban greenery and the ES they provide play a particularly important role in adaptation measures for open spaces. Many studies have shown the potential of urban green spaces to optimise the local urban climate (Mathey et al. 2011, Gaffin et al. 2012, Park et al. 2017, Klemm et al. 2018, Henninger and Weber 2019). Here the potential temperature reduction depends on the size and structure of the respective urban green as well as the availability of water and can vary over the course of the day (Mathey et al. 2011, Park et al. 2017, Henninger and Weber 2019). For example, large-crowned trees provide shade for improved thermal comfort during daytime hours, whereas large-scale lawns boost night-time cooling (Upmanis et al. 1998, Shashua-Bar et al. 2009, Bowler et al. 2010, Spronken-Smith and Oke 2010, Coutts et al. 2015). The existence and surface characteristics of blue elements, for example, small water bodies or fountains, can also help the local climate to adapt (Völker and Kistemann 2011, Speak and Zerbe 2020). For the sustainable planning and implementation of adaptation measures, parameters such as the characteristics of blue and green elements have thus to be closely considered. While there already exists a breadth of knowledge on climate change adaptation measures and the potential benefits to the local climate (Müller et al. 2013 Municipality of Vienna 2018), this is not reflected at the practical level of implementation. A study by Araos et al. (2016), for instance, tracked the climate change policies of 401 urban areas (with > 1 million inhabitants) around the world by analysing reported adaptation initiatives. The authors found that only 15% of the cities had introduced any adaptation initiatives, while another 18% reported that plans for adaptation policies were being drawn up (Araos et al. 2016). A survey conducted by the German state of Baden-Württemberg showed that not all municipalities were sufficiently aware of the issue of climate change adaptation or of suitable approaches to implement respective measures (LUBW (Landesanstalt Für Umwelt Baden-Württemberg) 2020). One explanation for this deficit is that climate change adaptation has yet to be established as a municipal task (LUBW (Landesanstalt Für Umwelt Baden-Württemberg) 2020). In Germany, for example, a suitable climate change adaptation law is still being drawn up (UBA (Umweltbundesamt) 2021). Furthermore, the adaptation process is hampered in many municipalities by a lack of resources, i.e. staff and expertise (LUBW (Landesanstalt Für Umwelt Baden-Württemberg) 2020). In their study, Otto et al. (2021) showed that city size plays a key role in the development of local climate policies: large cities, in particular, have greater capacities for such tasks. Their results also indicate that, while German cities with dedicated climate change policies tend to be committed to adaptation, they are not always leaders in this field (Otto et al. 2021). Clearly, it is important that detailed knowledge derived from research into adaptation options be integrated into planning practice (Baumüller 2018). Yet the findings of relevant studies are frequently not designed or prepared for easy application in everyday planning tasks (Baumüller 2018). Many guidelines are extremely comprehensive and not suitable for use by planning offices, which are often limited in time and resources. Often, there is a lack of any guidelines on which measures are best suited to particular areas and problems. Here digital planning tools can be of great benefit, providing a simple, straightforward interface for planning institutions and municipalities to make quick decisions (Van Oijstaeijen et al. 2020).

This study investigates various tools designed to facilitate the planning and implementation of climate change adaptation measures. Here, we understand the term “tool” in its standard usage in the field of informatics, namely a small programme that performs specific tasks for an operating system or application programme. Generally, tools are easy to understand and require input data to produce output data. In the following, we use the term “tool” to refer to a digital tool that aids the planning and implementation of climate change adaptation measures, as well as supporting decision-making by identifying potential vulnerabilities and suggesting possible adaptation measures, optimally by means of visualisation and quantified values. In this way, such tools should not only simplify the identification of measures (*Which measures are most suitable*?), but also support the associated decision-making processes by providing further argumentation for their realisation. Ideally, tools should also be able to identify and communicate additional co-benefits of measures in addition to the climate change adaptation effect, for example, the simultaneous promotion of different ES through the implementation of certain measures (Matthews et al. 2015).

Our review of existing planning tools at the national (for Germany) and international level is conducted on the basis of diverse criteria. As such tools are designed to aid planning and the realisation of appropriate measures, we consider the target group to be urban planners employed by professional practices, as well as municipal authorities. The analysis aims to answer the following questions: Which optimisation potentials can be determined for existing tools and which research gaps can be identified? After presenting and discussing the results of the analysis, we offer some general recommendations for tool development. Most existing tools for the reduction of urban heat reveal a lack of micro-climate simulations or are poorly transferable to other regions. Of course, such tools always have to make a trade-off between transferability and accuracy. These findings will be further developed and reflected in the creation of a dedicated tool within the framework of the project “HeatReslientCity II” (HRC II, http://heatresilientcity.de/en/). At the end of the paper, we present a concept for such a web tool designed to support heat adaptation planning at urban site scale (here: spatial resolution level smaller than 20 m, after Reinwald et al. 2019) in or around buildings. This tool is intended to present the impact of different adaptation measures on open space, as well as climatic conditions inside buildings. In addition to human-bioclimatic effects in open spaces, such as the reduction of heat, the tool will also identify other co-benefits, such as improved ES in order to support the decision-making process.

Methods

The review and assessment of existing planning tools consisted of four steps, illustrated in Fig. 1. This procedure was based on the method of Van Oijstaeijen et al. (2020), who conducted an analysis of green infrastructure assessment tools. Below, we explain the four working steps separately.

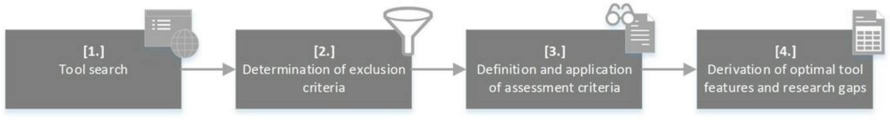

Figure 1.

Overview of working steps.

Tool search (working step 1)

Assuming that urban planners (our target group) are likely to seek tools for their daily work using a search engine rather than via scientific papers, we decided to use the world's most popular such engine for our study, namely Google search (Statcounter 2021).

A systematic Google search was conducted from September to October 2020. German and English search terms were used to locate national and international tools. During each search, the individual results were screened to see if a relevant tool was listed on the indicated web page. Here, the first step was to check for the terms "tool" or "toolbox". Then we assessed whether the "tool" dealt with heat stress and respective adaptation measures in the city. While this was true of some tools, others were described as being designed for other fields such as "energy" or "rainwater management"; in such cases, they were excluded from further analysis. If a tool were merely referenced, the provided link (or Google search) was used to search for the tool until the correct website was found. If several tools were listed on a resulting website or if reference were made to further tools, these were all subject to an immediate assessment and, where relevant, included in the analysis. Due to the high number of results, with frequent duplications as well as irrelevant information, the search process was declared finished for each search term after Google issued the message: "In order to show you the most relevant results, we have omitted some entries very similar to the […] already displayed. If you like, you can repeat the search with the omitted results included" (see Table 1).

In addition, a literature search was conducted on articles published on the *ISI Web of Science* website using the search terms "heat resilient city" AND "tool" and "heat adaptation city" AND "tool". Neither of these searches resulted in additional tools for analysis.

Table 1.

Overview of terms used for the Google search, the number of pages indicated by Google as most relevant and the total number of results.

Search terms	***Termination of search after Google displayed the most relevant results***	***Total number of results indicated by Google***
“Tool Hitze resiliente Stadt” [*engl. tool heat resilient city*]	Search results ended on p. 11	~ 276,000
“Tool Klimaanpassung Stadt” [*engl. tool climate change adaptation city*]	Search results ended on p. 13	~ 27,400
“Tool klimaresiliente Stadt” [*engl. tool climate change resilient city*]	Search results ended on p. 14	~ 14,700
“Tool hitzeangepasste Stadt” [*engl. tool heat adapted city*]	Search results ended on p. 12	~ 1,500
“Tool heat resilient city”	Search results ended on p. 21	~ 20,200,000
“Tool heat adaptation city”	Search results ended on p. 11	~ 45,100,000

Determination of exclusion criteria (working step 2)

The next step was to determine exclusion criteria to refine the search results and locate the tools relevant to the topic. If one of these criteria were found to apply to a tool, it was excluded from further analysis. The exclusion criteria are listed and briefly explained in Table 2 (note: the ordering has no significance).

Table 2.

Exclusion criteria for selecting tools for further analysis.

Exclusion criteria	**Short explanation**
(1) No city reference	Tools should focus on cities.
(2) Wrong topic	Tools should relate to the topic of heat.
(3) Insufficiently described	There is insufficient information for a further analysis.
(4) Still under development	The tool is still under development.
(5) No city-, district- or site-level *	The tool cannot be applied at the city-, district or site-level.
(6) No tool	Not a tool in the sense of the adopted definition (see Introduction).
(7) Outdated (no functionality)	The tool does not work/the website is no longer available.
(8) No climate change adaptation measures	The tool does deal with heat stress and climate change adaptation measures.

* Derived from Reinwald et al. (2019), the classification lists three urban levels (or scales): the neighbourhood (here “site”) level, which operates at a spatial resolution of 0.5 - 20 m; the district level, which operates at a spatial resolution of 20 - 200 m; and the city level, operating at a spatial resolution of 100 m - 1 km.

Definition and application of assessment criteria (working step 3)

After determining the exclusion criteria, it was necessary to define assessment criteria. These were used to evaluate the performance of the selected tools. Clearly, the criteria had to reflect those features that a tool must possess for everyday use in planning heat adaptation measures at city, district or site level. To this end, we chose the list of criteria for a useful planning tool suggested by two focus groups of 15 participants active in several fields of urban planning and decision-making, as recorded in the study by Van Oijstaeijen et al. (2020). However, due to the divergent objectives of the tools discussed in Van Oijstaeijen et al. (2020) (*values of green infrastructure in general*) and our research (*focus on heat stress*), some of these criteria were modified, omitted or replaced. The assessment criteria applied here are detailed in Table 3. Further, the necessary data input and resulting output for each tool was considdered and summarised and are supplied in the supplementary material (Suppl. material 2). The complexity of data gathering is reflected in the expertise-rating of each tool considering whether expert knowledge is needed for data gathering or not.

Table 3.

Criteria for tool assessment.

Assessment criteria	Description
Free of charge	For everyday use, it is necessary that a tool be free of charge and freely available to everyone. If this is the case, a tool was rated “++”; otherwise “-”.
Expertise	Since authorities such as city planning departments often lack expertise in a wide range of topics (Van Oijstaeijen et al. 2020), it is beneficial if tools can be used by all stakeholders without the need for specialised training. Thus, following Van Oijstaeijen et al. (2020), tools that do not require any expertise for reliable results were rated “++”; tools that do not require expertise for general results, but require input data for the specific local context and which may thus require expertise from specific disciplines, were rated “+”; tools that do not require expertise for general results, but require the input of geo- and climate data by the developers for reliable results were rated “0”; tools where the calculations are performed by the developers were rated “-”.
Scale	According to Van Oijstaeijen et al. (2020), it is important that planning tools operate at different scales to accommodate variations in the size of project areas. Following Henninger and Weber (2019), bioclimate and local heat stress must often be analysed at very small scales. For this reason, tools that operate at the district or site level were preferred in our analysis. However, tools that operate above this scale were not excluded, as such tools may be suitable for detailed analysis in some circumstances. The classification was based on Reinwald et al. (2019), which lists three scales in relation to the city: the neighbourhood (here “site”) level, operating at a spatial resolution of 0.5 - 20 m; the district level, operating at a spatial resolution of 20 - 200 m; and the city level, operating at a spatial resolution of 100 m - 1 km. Consequently, tools working at all scales were rated “++”; those suitable for site and district level were rated “+”; those suitable for district and city level were rated “0”; and those working only at city level were rated “-”.
Purpose of the tool	During the analysis, we determined that the criterion of scale does not give insight into the level of detail offered by a tool. Therefore, this additional criterion was introduced. Tools which analyse the microclimate and the effectiveness of measures were rated “++”; tools that merely record the effectiveness of measures were rated “+”; tools that only carry out a rough screening were rated “-”.

Assessment criteria	Description
Vulnerability	An optimal planning tool should include a vulnerability analysis. Here, this means an assessment of the current stress situation in the project area, i.e. we considered whether a tool tests the stress situation in any way. This was evaluated using: a) socio-economic data; and b) the presence of areas of heat stress or some kind of thermal stress in terms of higher temperature. The latter is considered more important for the analysis. A tool which covers both categories was rated “++”; if only one category is covered, temperature indices were preferably rated with “+”, socio-economic data was rated with “0”; no coverage of vulnerability was rated “-”.
Factors of local heat stress	To get an impression of the extent of the stress situation due to excess heat, we recorded whether intensifying factors (e.g. during night-time hours: building design and for daytime hours: soil sealing) and heat reducing factors (subdivided into high vegetation, low vegetation and water elements) were considered during the tool development or directly in the tool itself. Optimally, a detailed analysis of the climatic situation should encompass all factors. The recording of all factors was rated “++”; the recording of all factors, except water elements was rated “+”; the exclusion of the factors water elements and high vegetation with “0”; and no recording of factors was rated “-”.
Subject of quantification	In addition to the purpose of the tool, this criterion allows an assessment of the scope of the evaluation. Clearly, a planning tool designed to map measures of heat-resilient climate change adaptation should quantify vulnerability and measure the degree of effectiveness. While the measuring of effectiveness is preferred over vulnerability in our assessment due to the focus on mapping measures, a vulnerability assessment is also considered desirable. Furthermore, it was recorded here whether a tool offers recommendations for measures, even if this does not necessarily involve quantification (therefore listed in brackets). In order to be subject to further analysis, a tool had to recommend adaptation measures. Thus, tools meeting all three criteria were rated “++”; those offering an analysis of measure effectiveness and giving recommendations were rated “+”; those with an assessment of vulnerability and measure recommendations were rated “0.”
Quantification	Van Oijstaeijen et al. (2020) point out that quantified results are extremely important for public decision-making. Due to economic considerations and a lack of awareness of the significance of green structures and their value for society, decisions in planning processes often overlook the issue of green spaces (Böhm et al. 2016). In order to convey the value of green and blue infrastructure in urban planning, it is necessary to capture this as comprehensively as possible in order to provide arguments for its implementation. For simplicity, no distinction is made here between the quantification of vulnerability or the effectiveness of measures. Quantification can be based on socio-economic indicators (e.g. mortality rates or reduction of hospitalisation), biophysical indicators (e.g. thermal stress indices) or monetary values, optimally supplemented with data on additional co-benefits. Tools may also quantify data by simple categorisation or scores. Accordingly, tools that output several of the categories were rated “++”; those delivering only one category were rated “+”; and those quantifying by means of scores and categories as a minimum requirement were rated “0”.
Scenarios	The modelling of scenarios in a decision-support tool can help compare planning states as well as assist in deriving the best possible measures. In the best case, the current state is represented in addition to planning scenarios. Tools with this ability were rated “++”. Tools that merely represent planning states while neglecting the current state are usually orientated on a “worst case” scenario; these were rated “0”. Since our research focus is on tools in the field of planning, representation of only the actual state is considered insufficient and rated “-”. While the modelling of RCP scenarios[1] is considered a useful function, this is only listed for information purposes and was disregarded in the evaluation.

Assessment criteria	Description
Transferability	As each study area is subject to local conditions, these will clearly affect the impact of adaptation measures. While tools are usually developed for specific project areas and thus specific conditions, transferability to other geographic and socio-economic areas is often possible using benefit transfer methods. Here, it is often very helpful to consider the methodology behind a tool. A tool which demands local geodata for its application (thus indicating greater reliability of results) was rated "++". Tools that are easy to generalise using benefit transfer methods, but which can be adapted to local conditions using local data, were rated "+". Tools relying solely on benefit transfer methods were rated "0"; those developed for specific areas and which are not transferable to other regions were rated "-".
Time requirement	Since a tool should be designed for everyday use in planning, it is helpful if only a short training period is needed and results can be obtained quickly. In this sense, tools that can be used immediately, i.e. with no training period and which give speedy results were rated "++"; tools with a certain training period, but fast output of results were rated "+"; those with increased time required for data acquisition or processing were rated "-".

[1] RCP = Representative Concentration Pathway; RCP scenarios are based on multi-gas emission scenarios and are labelled to reflect a possible range of radiative forcing values in the year 2100 relative to pre-industrial values.

A 4-point scale was used to evaluate the performance of the selected tools according to each assessment criteria. These ratings were: "++" for very suitable, "+" for suitable, "0" for acceptable and "-" for unsuitable as a decision-support tool in the sense of this study. For additional information gathering on the selected tools, we consulted the respective manuals, websites, press releases, video tutorials and scientific publications on the methods or case studies.

Derivation of optimal tool features and research gaps (working step 4)

Based on the analysis and comparison of the different tools, we then identified optimisation potentials, as well as further research gaps. These will be detailed in the discussion section.

Results

A total of 58 tools were identified by the search process (listed in Suppl. material 1). After applying the exclusion criteria, the remaining eight tools were subject to detailed analysis. These tools are designed to aid the planning and implementation of climate change adaptation measures in cities. Fig. 2 provides an overview of the selected group of tools, including a brief description of each.

It is striking that seven of the eight tools are from Europe (see Fig. 2). Three tools are specifically focused on thermal stress, two also consider other extreme events and the remaining three are very comprehensive in the topics they consider. Most of the tools were released or updated in 2020.

Tool	Developer	Country of development	Tool type	Region of application	Short description	Considered topics	Latest version	Links
GREENPASS	GREENPASS GmbH	Austria	Web tool	Worldwide	Urban climate simulation. Internationally applicable all-in-one planning, optimization and certification tool for climate resilient urban planning and architecture.	Climate, water, air, biodiversity, energy, costs	2020	https://greenpass.io/de/, 29.12.21
CLARITY Advanced Screening Tool	17 EU Clarity Partner	Austria	Web tool	Europe	The characteristics of different land cover types are used to estimate and present heat hazards, population exposure, and the magnitude of heat wave impacts on populations under different temporal periods and RCP scenarios.	Heavy rain floods, heat waves / heat stress.	2020	https://myclimateservices.eu/, 04.12.20
INKAS-NRW/ INKAS	Landesumweltamt (LANUV), Deutscher Wetterdienst (DWD) and Stadt Bonn	Germany	Web tool	North rhine westphalia / Germany	Presentation of the effect of different urban climate change adaptation measures in differently structured urban quarters with regard to summer heat periods, as well as estimation of the risk potential for summer heat stress of the characteristic urban development types.	Heat stress	2020	*Klimaanalysearte:* www.klimaanpassung-karte.nrw.de, 29.12.21 *INKAS:* https://www.dwd.de/DE/leistungen/inkas/inkasstart.html, 29.12.21
Future Cities Adaptation Compass	Future Cities partnership (8 partner from 5 EU countries)	Germany	Excel tool	Europe	To guide the process of identifying, assessing, documenting, and discussing adaptation measures using a predetermined assessment and documentation structure, as well as a wealth of background information.	Population, Infrastructure, Development, Local Economy, Natural Resources each in relation to extreme events.	2014	http://www.future-cities.eu/project/adaptation-compass/, 29.12.21 *German version via E-Mail request*
Betroffenheitswizard	Bundesinstitut für Bau-, Stadt- und Raumforschung	Germany	Web tool	Germany	By assigning the expression of the climate signal and the sensitivity of a factor at the present time and a future time, an impact assessment is provided for the impact consequences in 10 topic areas.	Health, energy, water, infrastructure, transport and traffic, open and green spaces, air hygiene, tourism and cultural heritage, agriculture, forestry	2016	https://www.klimastadtraum.de/DE/Arbeitshilfen/Stadtklimalotse/LotsenNutzen/BetroffenheitsWizard/wizard_node.html, 29.12.21
C40 Heat Resilient Cities Benefits Tool	Ramboll	Denmark	Excel tool	Worldwide	Quantification of human health impacts and associated socioeconomic cost reductions from adaptation measures to reduce urban heat stress.	Heat stress	2020	https://ramboll.com/media/rgr/measuring-benefits-of-urban-heat-adaptation, 29.12.21
Adaptation Support Tool	Deltares	Netherlands	Web tool	Version 1: worldwide Version 2: Netherlands	Support collaborative planning workshops on spatial adaptation of the urban environment by locating and quantifying nature-based (green-blue) and traditional (gray) adaptation measures.	Heat stress, drought, flooding, water security.	2020	*V1:*https://crctool.org/en/, 29.12.21 *V2:*https://kbstoolbox.nl/nl/, 29.12.21
Microclimate and Urban Heat Island Mitigation Decision-Support Tool (UHI-DS)	Cooperative Research Center for Low Carbon Living	Australia	Web tool	3 sample districts in Sydney	Integrating scientific models into a 3D web tool to analyze the urban heat island effect and the impact of adaptation measures on individual properties and the entire district for three example Sydney districts.	Heat stress	2019	http://uhimitigationindex.be.unsw.edu.au/uhitool/index.html, 29.12.21

Figure 2.

General information on the selected tools.

Sources for further analyses: ***Greenpass*** (Greenpass GmbH 2020, Kraus and Scharf 2019, Reinwald et al. 2019, Grünplan Landschaftsarchitekten 2022, Greenpass GmbH 2022a, Greenpass GmbH 2022b); ***Clarity Advanced Tool*** (Havlik 2020, Havlik et al. 2020, Urban Digital 2020, de Wit et al. 2020); ***INKAS-NRW/INKAS*** (Buchholz 2019, MULNV NRW (Ministerium Für Umwelt, Landwirtschaft, Natur- und Verbraucherschutz des Landes Nordrhein-Westfalen) 2020, DWD (Deutscher Wetterdienst) 2022, LANUV NRW (Landesamt Für Natur, Umwelt Und Verbraucherschutz Nordrhein-Westfalen) 2022); ***Future Cities Adaptation Compass*** (Lippeverband 2020); ***Betroffenheitswizard*** (only the tool itself, since no manual or similar exists); ***C40 Heat Resilient Cities Benefits Tool*** (C40 and Ramboll 2020); ***Adaptation Support Tool*** (Van de Ven et al. 2016, Deltares 2019, Deltares 2020a, Deltares 2020b, Deltares 2020c, Deltares 2022); ***Microclimate and Urban Heat Island Mitigation Decision-Support-Tool (UHI-DS)*** (Ding et al. 2019).

Fig. 3 summarises the assessment criteria (described in Table 3) in a qualitative and objective way. A more detailed presentation of input data can be found in Suppl. material 2.

	Free of charge	Expertise	Scale			Purpose of tool	Vulnerability		Factors of local heat stress		Subject of quantification	Quantification	Scenarios			Transferability	Time requirement
			C	Di	S		S	TI	HInt	HRed			R	AS	P		
GREENPASS		B	x	x	x	MC		x	Bu, Se	HV, LV, W	Vu, Ef, (MR)	Bio, Mon, S, Co		x	x	LD	3
CLARITY	x	NE	x			GS	x	x	Bu, Se	HV, LV, W	Vu, Ef, (MR)	Soc, Bio, Mon	x	x	x	LD	2
INKAS	x	NE		x	x	E		x	Bu, Se	LV	Vu, Ef, (MR)	Bio		x	x	NT	1
Future Cities	x	NE, (D)	x	x		GS	x				Vu, Ef, (MR)	Ct, S		x		BT (LD)	3
Betroffenheitswizard	x	NE	x	x		GS	x	x	Bu, Se	HV, LV	Vu, (MR)	Ct		x		BT	1
C40	x	NE, (D)	x	x		E	x	x			Vu, Ef, (MR)	Soc, Bio, Mon	x		x	BT (LD)	2
Adaptation Support Tool V1	x	NE, (D), (GIS), (T)	x	x	x	E					Ef, (MR)	Bio, Mon, S			x	BT (LD)	1
Adaptation Support Tool V2	x	NE, (D), (T)	x	x	x	MC		x	Bu, Se	HV, LV	Vu, Ef, (MR)	Bio, Mon, S, Co		x	x	NT	1
UHI-DS	x	NE	x	x	x	MC		x	Bu, Se	HV, LV, W	Vu, Ef, (MR)	Bio, Ct		x	x	NT	1

Expertise: B = Expertise needed for calculations. GIS = Expertise needed to insert local geodata and climate data; D = Expertise needed for input data (e.g. results, targets); T = Expertise needed for tool application; NE = No expertise needed; (...) indicates a recommendation for expertise although this is not mandatory for tool usage.
Scale: C = City; Di = District; S = Site.
Purpose of the tool: MC = Microclimatic situation; E = Effect of adaptation measures; GS = General screening.
Vulnerability: S = Socio-economic data; TI = Temperature indices.
Factors of local heat stress: HInt = Heat intensifying factors; Bu = Buildings; Se = Soil sealing; HRed = Heat reducing factors; HV = High vegetation; LV = Low Vegetation; W = Water elements.
Subject of quantification: Vu = Vulnerability; Ef = Effectiveness of measures; (MR) = No quantification but measures recommended.
Quantification: Soc = Socio-economic data; Bio = Biophysical units; Mon = Monetarization; S= Scores; Co = Co-benefits; Ct = Categories.
Scenarios: R = RCP-scenarios possible; AS = Actual state; P = Planning state through realization of measures.
Transferability: LD = Local data; BT (LD) = Benefit transfer (specification through local data possible); BT = BenefitTransfer; NT = Not transferable.
Time requirement: 1 = no training needed; 2 = some training, fast results; 3 = Data acquisition or processing takes time.

Figure 3.

Overview of the analysis of selected tools regarding their performance in planning. The Table indicates two versions of the Adaptation Support Tool, which are quite different in their functions. The sources for the information given here are listed in Fig. 2.

	Free of charge	Expertise	Scale level	Purpose of the tool	Vulnerability	Factors of local heat stress	Subject of quantification	Quantification	Sceanrios	Transferablity	Time requirement
GREENPASS	–	–	++	++	+	++	++	++	++	++	0
CLARITY	++	++	–	–	++	++	++	++	++	++	+
INKAS	++	++	+	+	+	0	++	+	++	–	++
Future Cities	++	+	0	–	0	–	++	0	–	+	0
Betroffenheits wizard	++	++	0	–	++	+	0	0	–	0	++
C40	++	+	0	+	++	–	++	++	0	+	+
Adaptation Support Tool V1	++	0	++	+	–	–	+	++	0	+	++
Adaptation Support Tool V2	++	+	++	++	+	+	++	++	++	–	++
UHI-DS	++	++	++	++	+	++	++	+	++	–	++

Figure 4.

Performance evaluation of tools for planning activities.

Fig. 4 presents the described 4-point scale assessment of the tools, based on the defined assessment criteria. This subjectively compiled overview serves as a quick and intuitive summary for potential users (here: planners) to determine the suitability of a tool.

Discussion & optimal tool features

Tool assessment

All tools (apart from *GREENPASS*) are available free of charge, making them suitable and affordable for quick assessment (see Fig. 3). Tools that are quick to use are often designed in such a way that they also require little expertise. In fact, all tools, except *GREENPASS*, can be run without prior experience using default values and benefit transfer methods for a general assessment and exploration of measures and/or their effectiveness (see Fig. 3). These tools have the advantage of easy application to areas where data are scarce. Nonetheless, Van Oijstaeijen et al. (2020) state that such assessment tools should be used with care, claiming that users must ideally possess an extensive understanding of the underlying methods and limitations. The tools *Betroffenheitswizard* and *Future Cities Adaptation Compass* were designed as comprehensive screening tools, producing very general quantified values (see Fig. 3). While the effectiveness of measures is also addressed in *Future Cities Adaptation Compass*, the results are categories rather than concrete values. These two tools are primarily designed to identify options for municipal action with regard to climate change adaptation. The low spatial resolution of the *CLARITY* tool is also only designed for general screening, here with a focus on thermal stress (see Fig. 3). As this tool offers concrete as well as extensive quantification of vulnerability and adaptation strategies, it is suitable for a quick, if rough, assessment of the urban heat situation.

As the tools were mostly developed for specific areas, they have extremely limited transferability (e.g. *UHI-DS*). Those tools designed for a wider applicability usually employ benefit transfer or spatial proxy methods, giving generalised results and reducing the reliability of outcomes (Eigenbrod et al. 2010). Some tools attempt to improve the accuracy of their outputs by including some local data in the form of geodata or socio-economic data. However, such local datasets are usually very general, without a clear reference to the on-site microclimatic situation. Only three tools can accommodate local geo- or climate data. *GREENPASS* directly integrates climate data (based on landcover and land-use types) in the urban climate model (ENVI-met). The *CLARITY Advanced Screening* tool uses local open-source geo- and climate data for certain cities at a spatial resolution of 500 m² (which is too imprecise for site level). While developers can adapt the tool to other cities or to a more detailed resolution with the right datasets, this requires additional time and expertise (see Fig. 3). The *Adaptation Support Tool V1* (*AST 1*) can be adapted to local-specific climate data with the involvement of the developers in a rather time-consuming process.

With the exception of CLARITY, all tools were designed to investigate “heat stress” seen as the impact on the human well-being and health (along with some other issues). However, only three tools are able to assess the microclimatic situation, namely *GREENPASS*, *Adaptation Support Tool V2* and the *UHI-DS* tool, AST 2 and UHI-DS, but are not transferable to other cases. In Fig. 3, we also see that socioeconomic vulnerability is only investigated by the four tools operating at larger scales. Furthermore, *CLARITY* is the only tool to work with actual geodata on the local population. As inputs, *Betroffenheitswizard* and the *Adaptation Compass* require rather crude, non-specific data. *CLARITY* and the *C40 tool* are the only tools to use socio-economic data to analyse the impact of measures. Both tools completely neglect the localisation of, for example, social institutions of particularly vulnerable groups, such as kindergartens or nursing homes. *CLARITY* focuses solely on population density. While *C40* considers age structure, this is not for the purpose of localisation, but rather to calculate the likely spread of heat-related disease. The gathering of socio-economic data may be more important for the localisation of particularly vulnerable areas at the city and district level than at the site level.

On the other hand, almost all tools attempt to assess vulnerability to thermal stress, albeit in very different ways. One exception here is *AST 1*, which does not capture vulnerability via meteorological variables or socio-economical values. Like the *C40* tool, it cannot represent the actual climatic situation and, thus, only analyses the effectiveness of measures in comparison to a worst-case scenario. While the *INKAS* tool also only considers the effect of measures, the user has the option to estimate the actual situation via spatial analysis diagrams. Apart from *Adaptation Compass* and *Betroffenheitswizard*, all tools allow the planning status to be altered, which is very useful for planning decisions and to derive optimal solutions.

In general, it is helpful for planners if comprehensive outputs are offered, especially monetary values, in order to convince investors and decision-makers of the importance of implementing measures (Van Oijstaeijen et al. 2020). Except for *Adaptation Compass* and the *Betroffenheitswizard*, all tools use at least biophysical metrics. *INKAS* and the *UHI-DS* tool can only calculate temperature indices. While this may be sufficient to determine the thermal impact of a measure for planning purposes, such data are scarcely suitable to persuade investors or other stakeholders. For this reason, it is generally necessary to calculate monetary values in addition to biophysical metrics, as well as (where applicable) socio-economic data. These are all provided by five of the tools (see Fig. 3). *GREENPASS*, *AST 1* and *AST 2* are able to quantify investment and maintenance costs. Potential cost reductions – presumably particularly decisive for planning processes (e.g. reduction in hospital costs) – are provided as outputs in the tools *GREENPASS*, *CLARITY*, *C40* and *AST 2*. It should be noted that Fig. 3 does not indicate the scope of measures that tools can accommodate. While the measures in *GREENPASS* are presumably freely selectable, some tools are extremely limited in the measures that can be quantified. For instance, the *UHI-DS* tool can only analyse the impact of a few specified measures; the *C40* tool can evaluate only four rather generalised types of measure, all of which must be of a certain size; and the *INKAS* tool also considers only a fairly limited list of measures. In general, our analysis showed that almost no tool can be applied to small individual measures on small areas, such as a single tree, even though these can have a large local climatic effect (Westermann et al. 2021). While the effectiveness of such measures is probably difficult to evaluate for an entire district, they can clearly boost the well-being of local residents. *AST 2* is the most innovative in this sense, as it can take account of small individual measures and their effect via a PET map (Physiological equivalent temperature, Höppe 1999).

In almost all cases, the descriptions of the tools stated that they were developed especially for urban planners to support the decision-making process. Usually, (several) research institutions were involved in the development over a lengthy period. Consequently, the tools all show a high degree of sophistication. Unfortunately, most tools do not address the microclimate, which is so crucial for analysing the impact of heat stress on the well-being and health of urban residents. The accompanying documentation to the tools repeatedly points out that they cannot replace detailed urban climate simulations based on local data. Here the question arises whether detailed studies for smaller project areas are, in fact, necessary. Van de Ven et al. (2016), for instance, describe from experience that measures are often implemented in practice, based solely on their expected effect. Van Oijstaeijen et al. (2020) also point out that municipalities frequently lack the time and resources to conduct intensive evaluation processes at project level. The tools assessed here are generally intended for the early planning phases, when preliminary generalised values and outputs can help shape the later planning stages. However, there remains a risk of over- or underestimating the impact of various measures, leading to their (perhaps unjustified) acceptance or rejection.

Optimal tool features

In the following, our analysis results are used to pinpoint those elements which tools must possess in order to be useful to planners.

Currently, many tools neglect the microclimate. While temperature indices can be found in almost all examined tools, these are generally only used to roughly record the overall situation and are not localised, for example, via geodata. Clearly, the use of geodata can strengthen the scientific basis of results and save time in data gathering (Van Oijstaeijen et al. 2020). The use of local microclimate data by tools will certainly ensure the quick transferability of results to similar (climatic) conditions without having to undertake extensive data collection and simulations, when needed data are provided by the tool itself. However, we acknowledge that local climate data are often hard to obtain and availability can considerably differ depending on the area studied. This could hinder the user to take advantage of a tool. For a first evaluation of the overall situation, easy tools with a low demand of input data might also be very helpful, especially for users with less expertise. The *CLARITY* tool has adopted a good approach here by linking open-source datasets, although the spatial resolution is still too low to be able to map microclimatic conditions. In the course of the development of *AST 2*, a PET map covering the whole of The Netherlands was created to locate areas of heat stress. This comprehensive data can potentially help to express the biophysical effects of adaptation measures in a particularly meaningful way for decision-making processes. Further research is required to design ways of representing and assessing the microclimate and heat stress situation, based on simple, generalising features and conditions. Such approaches could certainly bring useful features to planning tools.

The consideration of small site scales is particularly useful when planning heat adaptation measures. Many of the tools presented here, however, operate on other scales, such as city or district level (see Fig. 3). When the micro-scale climate situation is neglected (as in most of the examined tools), only those heat reduction measures with a measurable effect on the entire neighbourhood can be modelled. Consequently, very small-scale or specific measures are ignored by tools, such as the greening of bus stops and the introduction of individual trees. Measures that can significantly improve the quality of life by reducing heat stress, but do not achieve a measurable effect for the whole neighbourhood, are virtually excluded from the outset. Here, further research is needed to formulate requirements for future tools to ensure a stronger focus on site scales. Often there is a lack of relevant studies and knowledge, as shown in the review by Brzoska and Spāģe (2020) of the evaluation of urban ES.

In addition, the recommended measures in the tools are presented in a generalised way. This can foster user engagement with the measures and, thus, constitute a learning effect. However, it can also lead to the user feeling overwhelmed, as it becomes difficult to determine which measure makes the most sense and which is most effective for any particular type of urban structure. In some tools, the measures are insufficiently described. The user, therefore, has to inform herself/himself extensively, a step which takes time and could lead to a loss of interest and information. Therefore, it would be better if highly specific measures were proposed. Almost every tool makes recommendations by linking together diverse features using filters or scores. Often, for example, the measures are linked to the potential for heat reduction or the building type. Combinations of different filters are more likely to be implemented in filterable catalogues of measures. The *AST* is the only tool that provides more precise recommendations by scoring a pre-selection of different characteristics of the environment (e.g. slope, soil availability, soil type), urban structure types (development type, fallow land, sports field, extensive green space, grey sealed area etc.) and objectives (e.g. heat reduction, drought reduction, flood safety). More specific results will be given if there is no multiple selection of characteristics for divergent areas, but in fact. only one area is considered in isolation and the information is adjusted to that one site. This could possibly be concretised in the *AST* or in a novel map-based tool by the user assigning concrete properties to individual sites in an area in a standardised way, enabling the recommendation of targeted measures. Certainly, this would require a considerable volume of input data for large areas; for small project areas, however, the time required would probably be fairly modest, thereby offering the user more concrete decision support. It makes sense to locate or link the advantages and disadvantages, the execution variants and examples briefly and precisely in the tool itself. A very detailed tool for measure recommendations could be created if the user inputs the most precise possible specifications of urban structure types and their characteristics, such as area size, degree of sealing, vegetation or similar.

Furthermore, monetary values could be expanded to support the decision-making process. Here, the tools apply different methods to quantify cost reductions in the health sector or the estimated costs of measures, for example. Since these values, in particular, could sway the decisions of investors, it makes sense to integrate as many such values as possible. However, most tools currently offer only a few such values.

Co-benefits provide further arguments for the implementation of green- and blue infrastructure in planning processes, yet these are hardly reflected in the investigated tools. Therefore, co-benefits could be included in a new tool, alongside socio-economic values, which should be considered more extensively. Our analysis also determined that the tools only address daytime heat stress while ignoring the nocturnal heat load, which is particularly important for physical and mental recovery (Baumüller 2008). Heat stress at night is only modelled in *GREENPASS* via the PET maps. This deficit could be remedied in a newly-designed tool. However, measures for heat stress at night may partly conflict with those intended to reduce daytime heat stress, for example, trees providing shade during the day can reduce ventilation and cooling at night (see Henninger and Weber 2019). It could prove challenging to reconcile these features in a tool designed to be as simple as possible.

Methodological limitations

Most of the assessed tools were developed in Germany and Europe; this can be attributed to the specific search terms, as well as the geographical location of our search. As previously mentioned, we made use of Google search to locate the investigated tools. This method was chosen as it reflects the likely approach of a typical planning office faced with limited staff and time. However, the use of the Google search engine raises a few uncertainties that should be pointed out. On the one hand, Google weights the search results on the basis of ranking systems and search algorithms (Google 2022). Further, the search is also influenced, for example, by the user's location, the topicality of the web pages and other factors. It is, therefore, questionable whether the same results would be displayed if the method were repeated later at a different location. It is also uncertain whether all relevant web pages are actually displayed by the search engine. In the applied method, the search for the respective search term was declared to have ended when – according to Google – all of the most relevant results were displayed. This step is determined by Google's search algorithms. However, since the number of non-relevant search results (according to Google) appeared far too extensive for any manual analysis (see Table 1), the most relevant Google results were taken as sufficient. Ultimately, the search results will closely reflect the chosen search terms. The individual search results and, where applicable, their subpages were each screened for relevant tools. Although this procedure was carried out very conscientiously, it cannot be ruled out that some relevant information was missed, for example, due to non-functioning links. Regarding the search method and its uncertainties, the selected tool list does not claim to be exhaustive. The platform *Web of Science* was consulted for completeness in order to validate our search method. In addition, it became clear during the analysis that scientific articles simply do not exist for all tools; therefore, the fact that websites and manuals must necessarily serve as sources of information, reinforces the validity of the simple Google search.

Regarding the analysis of the selected tools, it should be pointed out that a large number of the assessment criteria were drawn from those identified by Van Oijstaeijen et al. (2020). In the future, however, the process of criteria selection should ideally involve potential users of the planning tools. Additionally, the assessment criteria had to be greatly simplified to enable a meaningful evaluation. There is some interdependency between individual criteria, such as expertise and time requirement, which needs to be taken into account when interpreting the results. Another limitation is that the evaluation of the tool performance (see Fig. 4) was solely conducted by the authors of this study. A larger-scale survey including potential users of the tools (planners) would certainly increase the reliability of the assessment of tool performance. This should be considered in future work. In addition, we must point out that GREENPASS could only be evaluated to a limited extent as the relevant resources and the tool itself were not freely available.

In general, the term “tool” is all encompassing, covering diverse planning tools and instruments that can be either digital or analogue (guidelines, maps, brochures etc.) and many results were excluded. For this study, therefore, we had to give a closer definition of the meaning of “tool” (see Introduction). This reduced our sample to a small group of tools (eight in total, see Fig. 2) that could be considered for use in everyday planning.

Concept for a new web tool

The tool-comparison and analysis in this study serves as a basis for developing a new web tool which focuses on heat stress. It will evaluate the effectiveness of specific heat adaption measures in open space, as well as for indoor conditions. The results of the literature-based tool-review and assessment were used to frame a first concept of a new web-tool which is being developed as a part of the joint project “HeatResilientCity II” (http://heatresilientcity.de/en/).

The preceding analyses have shown that many tools do not require prior experience, what supports the idea of easy-to-use tools. Still, many tools show a deficit in the overall transferability and were only developed for specific areas. Tools which are not developed for a special area usually give generalised results. Some tools try to overcome the generalisation by implementing local geodata. However, the microclimatic situation is, in most tools, considered in an insufficient manner. The criteria of the preceding tool-assessment (Table 3) were used to define requirements on the new tool under development. The assessment of the tools discussed showed a need for improvement in the following aspects, in particular: (1) assessment of heat stress itself using a human-bioclimatic index and not only air temperature; (2) heat stress assessment at the urban site scale and with a high spatial resolution; (3) consideration of different daytimes as heat stress is variable according to the time of day; (4) consideration of different scenarios of sealing, building, planting and (5) overall transferability of the tool on to different regions. All these criteria are, therefore, addressed during the conception of the new tool.

All these points raised will be regarded in the new tool. Their implementation will be described in the following. The new tool will make use of detailed and highly resolved microclimate simulations for assessing the heat stress to generate accurate results (first requirement). The microclimate simulation data for the indoor and outdoor situations will be already implemented in the tool. Thus, there is no need for the user to search and implement further geodata. Further, the tool will be based on a pre-defined selection of different urban site scenarios at a micro-scale whose effects on their microclimate were simulated. That allows the comparison between several scenarios which can either represent initial situations, as well as different heat adaptation measures (second and fourth requirement). Additionally, heat stress will be assessed not only for daytime, but also for night-time and evening (third requirement). Looking at the existing tools, heat stress at night-time is only considered in the GREENPASS tool using the PET. Therefore, it was an important criterion to assess the heat stress for urban residents during different times of the day as this information is not given by most of the present tools. Last, but not least, the tool will be transferable to areas having a climate similar to the climatic conditions used for the simulations (fifth requirement). It will not be limited to a certain research area. Most of the existing tools do not guarantee transferability and are, therefore, very limited regarding their potential use. With a transferable tool, the number of users might grow significantly.

The new tool will provide digital support for the planning and implementation of climate change adaptation measures (with a focus on heat adaptation) at district and site level. In particular, users will be able to visually map and assess the potential impacts of specific heat stress adaptation measures. It is intended to serve as a planning support tool for municipal employees (e.g. within city planning and environmental agencies), as well as an information platform for private users and will also benefit from the trans- and interdisciplinary knowledge generation and methodological innovations gained in the first phase of HRC on urban climate and heat stress, indoor climate and ecosystem services (Westermann et al. 2021a). The utilisation of the HRC tool will bring added value by aiding the selection of appropriate measures to improve the urban climate and indoor comfort, protect and promote urban greenery, as well as foster a more sustainable, social-ecological urban development. To this end, it will generate supporting arguments for decision-making processes on adaptation measures, as well as recommendations for private users on how to behave during periods of excess heat or how to improve the indoor climate.

To ensure that the HRC tool has a user-friendly design and simple interface, it is being developed together with actors from the municipal administration. In the initial development phase, a small survey was conducted online within the administrations of the German partner cities Dresden and Erfurt to identify the requirements and wishes of potential users for such a planning tool. A total of twelve employees from the Departments of the Environment, Building, City Planning and Health participated in the survey. One desired output indicated by the results would be detailed statements on the heat reduction effects of individual measures. Moreover, the users expressed a particular interest in the evaluation of measures related to tree planting, as well as unsealing. Regarding indoor adaptation measures, the users identified exterior sunshades and open windows for nocturnal passive cooling by natural ventilation as adaptation measures that should be analysed. In the near future, a prototype version of the tool will be tested by potential users, whose feedback will be used for further development and optimisation. The adoption of a type-based approach, for example, ecosystem types (as discussed by Brzoska et al. 2021) will ensure the general transferability to other urban sites. The results of the survey, as well as the presented review of existing tools will help to specify the requirements of the HRC tool, which will be taken into account during development. Future users will be able to pick the measure they want to assess out of a given selection and will receive detailed information on its effectiveness for their chosen initial situation. The assessment output will be in the form of an easy-to-understand traffic-light system (e.g. from red for low effectiveness to green for high effectiveness). Moreover, the user will be provided with further information regarding the optimal measure in their case, as well as information about which administrations and actors are important for its implementation. A summary of results can be easily saved for later use to aid communication within decision-making processes. The HRC tool, however, does not give any indication of the potential cost of realising specific measures. In the first project phase, attempts were, in fact, made to feature and examine the costs of heat adaptation measures (Westermann et al. 2021a); these, however, are strongly dependent on the external framework conditions and, thus, difficult to transfer.

The tool will combine three sub-components: “open space thermal comfort”, “ecosystem services” and “indoor thermal comfort” (see Fig. 5, although “ecosystem services” may end up being included within “open space thermal comfort” in the final tool).

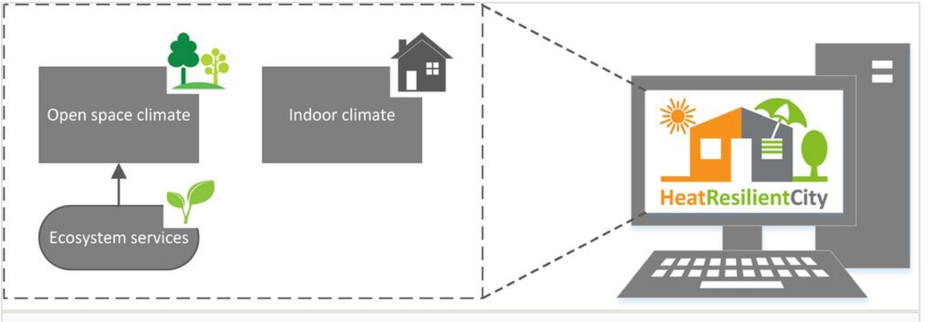

Figure 5.
Components of the HRC tool.

Open space thermal comfort

This component will assess the effectiveness of different adaptation measures in reducing urban heat. Their impact will be evaluated with regard to human heat stress, which encompasses short- and longwave radiation, air temperature and humidity, wind speed and direction. Here we make use of the Universal Thermal Climate Index (UTCI, Bröde et al. 2011, Jendritzky et al. 2011, Błażejczyk et al. 2018), currently one of the most frequently applied indices to measure heat stress. The tool component “open space thermal comfort” is based on urban microclimate simulations created by the model ENVI-met 3.1 (Bruse and Fleer 1998, Bruse 1999). Here, areas of size 12 x 12 m representing certain initial conditions and areas representing certain adaptation measures (e.g. increasing the amount of trees) were extracted from real-world simulations (Ziemann et al. 2019). The corresponding UTCI values were determined from these simulation results (Westermann et al. 2021). From a pre-selection of areas obtained in this way, the user can first select the one which best matches the target area whose thermal comfort is to be improved. In a next step, the user can select an area best matching the adaptation measure to heat s/he wishes to apply. Both chosen areas are visualised and a verbal description supplied. The evaluation of the effectiveness of the measure is based on the difference in UTCI between the two chosen areas (i.e. with and without the adaptation measure). As the tool output, the user is informed about the effectiveness of the chosen measure by means of a traffic-light rating system for three different hot summer days (mid-June, mid-July and mid-August) and three different times of the day (the evening, early morning and average conditions over mid-day). This is complemented by a short statement and some further details, where necessary (e.g. if the adaptation measure has little thermal effect, but may be still useful for other reasons). In addition, the difference in UTCI is reported, as well as the stages of thermal stress for both chosen areas. This concept will be implemented to evaluate the effect of individual measures of limited scope, as well as to assess the effect of heat adaptation measures on city streets (e.g. the planting of street trees). Generally, it will be also possible to assess the effect of measures which could potentially *increase* the heat stress suffered by residents (e.g. when trees are cut down). It is important to note that the “open space thermal comfort” component will provide some preliminary quantitative results that are much more useful than the mere qualitative statement “Urban green is good”, but which cannot replace detailed simulations of the urban climate in a special situation and for a real or planned district. The tool will be supplied with a manual, which comes in two versions (one shorter and one providing more details).

Ecosystem services

When the tool is ready, this component will probably end up being a subcomponent of the “open space thermal comfort”. It will provide the user with a description and evaluation of further co-benefits provided by certain heat adaptation measures and, thus, create a more comprehensive view of their diverse impact (here: on ecosystem services).

The ES assessment of the pre-defined model areas (which are also used for the open space climate simulation) follows the approach developed by Brzoska et al. (2021). This was transferred into practical implementation after being developed in the first phase of the HRC project. The approach applies a multi-criteria decision-making process to derive results on the provision of ES in a certain area, specifically the services of “passive recreation” and “nature experience”. In addition, other co-benefits, such as carbon storage and biodiversity, are identified and their individual function briefly described. In this way, the tool will offer qualitative statements on their function as impacted by the chosen measures, as well as a more detailed assessment of the supply of the ES “passive recreation” and “nature experience”. The results of the ES assessment could serve as an important additional aid to the decision-making processes for the potential realisation of certain measures.

Indoor thermal comfort

The second main component of the tool assesses the impact of adaptation measures on indoor overheating in residential buildings. In a first step, the user will be able to assess the current indoor thermal state of a room by providing information on the building type, the exposure of windows and location of the room within the building, for example. Based on these data, the risk of overheating is visualised by means of a five-level traffic-light system (from red for very high risk to green for minimum risk). After defining the initial state of the room, the user can choose different heat adaptation measures, such as solar shading devices or green roofs. Application of the selected measure to the initial room conditions may change the intensity of overheating, indicated by a shift in the traffic light, for example, from red to yellow or green. The assessment of the initial risk of overheating and the adapted risk are both based on simulations of building performance and indoor comfort monitoring for different residential buildings conducted in the HeatResilientCity I and II projects, as well as other projects (Kunze et al. 2020, Schünemann et al. 2020b, Schünemann et al. 2020a, Ortlepp et al. 2021, Schünemann et al. 2021a, Schünemann et al. 2021b, Schiela and Schünemann 2021). It is important to note that the indoor climate component of the tool offers a *qualitative* assessment of the chosen room by means of the traffic-light system without giving any *quantitative* estimates of the effect of the heat adaptation measures. This limitation is due to the large number of parameters that influence the indoor overheating risk. For a more detailed, quantitative evaluation of the impact of heat adaptation measures for a specific room or building, we suggest the use of building performance simulations, where possible, for the entire building in order to take account of internal air exchange and heat transmission.

Conclusions

To deal with the increased frequency and intensity of extreme heat events in cities (as predicted by many studies, as well as the current IPCC report), adaptation measures are urgently needed at the local scale. This review has identified a range of existing tools for the effective planning and implementation of climate change adaptation measures. Such tools can help save manpower and time – both of which are usually scarce at the municipal level – in the selection of suitable measures. They can also assist areas with scarce data availability to plan appropriate measures. However, such tools are still rarely used in practice. The challenge here is to find ways of creating useful tools for everyday planning that are not overly generalised and which do not require user expertise. Tools have the potential to simplify the work process and also give some first rough estimates about needed measures, knowledge that can be particularly valuable in the conceptual planning phase. The outputs of tools, such as identifying suitable adaptation measures and their impact, as well as other co-benefits (e.g. improved ecosystem services), can support the decision-making process and promote climate-adapted, sustainable urban development. In the future, tools should increasingly make use of local (geo-)data; here, the application of "big data" could also play a major role in the years to come. Furthermore, decision-making processes can be greatly aided by estimates of the likely costs (and savings) if measures are implemented. We recommend that future tools should focus on small spatial scales, such as individual sites. In general, it is also advisable that practitioners help design tools to ensure their practicality in everyday planning activities. Here, the participation of user groups in the development process can ensure a well adapted and application-oriented solution.

The previous assessment of existing tools helped to point out several disadvantages in existing tools and serves as a basis for framing overall requirements on a new tool for assessing heat adaptation measures. With the development of the presented web-tool, needed improvements for tools addressing heat stress for middle-European conditions, as pointed out earlier, are achieved. For deviating climatic conditions, new data would have to be compiled. The special features of the tool compared with previous development are the assessment of heat stress using a human-bioclimatic index at the urban site scale and with a high spatial resolution, the consideration of different daytimes, consideration of different scenarios of sealing, building, planting and the overall transferability of the tool.The new tool partly fits in the gap between detailed climate simulations and only qualitative evaluation of adaption measures. Still, there is a large trade-off to make between overall transferability and output-accuracy of such a tool. It cannot replace detailed and accurate urban climate simulations for specific planning issues and is, rather, suitable to provide the user in practice with a first overview of the quantitative and qualitative effectiveness of adaptation measures to heat. A very detailed and area-specific heat stress assessment can only be carried out by individual microclimate simulations which consider local circumstances. However, this would not fit the overall concept of an open-access tool which tries to reach users with less scientific background and providing a first guess for the effect of adaptation measures. Considering that, the new tool will serve as an important support for decision-makers or administration offices to evaluate and implement heat adaptation in their planning, as well as local residents who just want to inform themselves. Not least, this tool (as well as other tools) helps to raise awareness of urban heat stress and climate adaptation and its role in future city planning.

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Author contributions

P.B. wrote the preliminary draft with the support of T.F., U.M., A.Z., C.S. and J.W. The review and analysis of tools was conducted by L.M.. A.Z., K.G. and P.B. supervised and gave valuable input to the analysis. All authors were involved in reviewing/editing the manuscript and approved the final version.

Conflicts of interest

The authors declare no conflict of interest.

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Supplementary materials

Suppl. material 1: Results of the internet search doi

Authors: Brzoska, P. & L. Maul
Data type: table
Brief description: The results of the internet search, including the exclusion criteria in the last eight columns. The tools highlighted in grey are those which were subject to an in-depth analysis.
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Suppl. material 2: Table of data inputs/outputs doi

Authors: Brzoska, P. & L. Maul
Data type: table
Brief description: Table of data inputs/outputs. This serves as a quick qualitative overview of the scope and complexity of the tools and a basis for the planning tool performance table (Fig. 3). The sources for this table are listed in Fig. 2.
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