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Promises and pitfalls of climate adaptation tools across the Mediterranean

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Promises and pitfalls of climate adaptation tools across the Mediterranean

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Abstract

Although tools for climate change adaptation have proliferated, there is relatively little evidence about who they are intended to serve and how well they are suited to respond to decision contexts. We synthesized an inventory of 122 tools and found that around 73% of these are relevant to adaptation in the Mediterranean. We then examined who they are designed for, what they support, and how well they are suited to respond to decision contexts. We argue that access is not the main challenge, but alignment is. The results show that tools operate in isolation, often bound to administrative rather than physical boundaries, and provide limited guidance for choosing appropriate applications. Multilingual support and pathways to integrate local data are uneven. We outline actionable directions to improve this developing ecosystem, including linking tools to each other and to planning processes, make assumptions explicit, and involving anticipated users in the design process. These steps can turn a large and growing supply of tools into a more coherent, context-aware, and usable resource for adaptation and planning across the Mediterranean.

Introduction

Climate change adaptation has emerged as one of the most critical challenges of the 21st century, driven by the growing recognition of the immediate and long-term impacts from climate variability and extreme weather events. The Intergovernmental Panel on Climate Change (IPCC) emphasizes adaptation as an essential complement to mitigation, addressing unavoidable changes already underway[1,2]. Although evidence of adaptation action is growing globally, progress remains uneven and insufficient relative to rising risks[3,4], and prevailing narratives around adaptation continue to underestimate the needs of the most vulnerable[5]. Despite this urgency, adaptation continues to be overshadowed by mitigation in climate policies and funding, with resources falling far short of what is needed to manage escalating climate risks[6,7]. Global adaptation funding and finance flows remain inadequate relative to the scale of need[6], especially considering the costs of planning, preparing for, facilitating and implementing adaptation measures to moderate impacts[8]. This imbalance threatens to leave communities and ecosystems increasingly exposed to the impacts of climate change, especially in areas highly vulnerable to climate change, where adaptation is most critical.

In the Mediterranean, climate adaptation is particularly critical due to the region's status as a climate change hotspot, experiencing warming at a rate 20% faster than the global average[9–14]. The Mediterranean's vulnerability is compounded by its high population density, particularly in coastal areas, rapid urbanisation, increasing socio-economic pressures, and a heavy dependence on climate-sensitive sectors such as agriculture, tourism, and fisheries[15–18]. Coastal

communities and ecosystems are especially at risk due to sea-level rise, erosion, and saltwater intrusion[19,20]. As of today, climate change already undermines livelihoods and economic stability in the Mediterranean by reducing labour productivity in key sectors such as agriculture and tourism, accelerating rural-to-urban migration, and deepening socio-economic inequalities[21–23]s. As is true globally, adaptation planning in the Mediterranean also remains limited, fragmented, and uneven[24–27]. Without targeted adaptation efforts, these climate impacts risk deepening vulnerabilities, inequalities and regional instability. Sector-specific evidence further illustrates the breadth of climate-sensitive adaptation challenges, spanning ecosystem conservation, crop management, irrigation, drought and freshwater scarcity, and flood protection[28–37].

Compared to mitigation, which operates with a relatively narrow technical-economic realm, such as energy and emission markets, adaptation intersects with more complex social realities, including livelihoods, local power structures, resource entitlements, and cultural factors[38]. Implementing adaptation is inherently complex because it requires tailored, context-specific approaches that are reshaped by local institutions, social dynamics, and uncertainties. When adaptation measures do not resonate with traditional practices, values, or locally perceived needs, they are unlikely to be effective or sustainable in the long term[39,40]. Funding is another major obstacle to implementing adaptation, since most climate adaptation strategies require substantial, long-term investments in infrastructure, ecosystem-based solutions, and institutional capacity-building, which often conflict with short-term political agendas[41,42]. While essential, international adaptation finance is often misaligned with local priorities, reinforcing dependency on external support and limiting the development of locally driven, context-specific solutions[43]. Ultimately, adaptation responses remain largely reactive rather than anticipatory, resulting in inefficient resource allocation and increased vulnerability over time[44]. Beyond financial and governance barriers, there are also physiological limits to adaptation. Human capacity to adapt to a warmer and more extreme climate is finite and may be surpassed as climate extremes intensify[45–47].

In response to the complexities surrounding climate change adaptation and its implementation, a wide array of tools has been developed to support decision-making and facilitate action across diverse contexts[48,49]. In this study, we define a climate change adaptation (CCA) tool as a "*context-specific combination of information and methods developed to support climate change adaptation planning, implementation, and monitoring at various temporal and spatial scales*". For this study, we operationalise this definition as publicly documented, operational and digitally accessible resources (e.g., web portals, dashboards, software packages, decision-support systems, early-warning services, or interactive guidance platforms) that implement this combination. The operational scope used for selection is described in the Methods section.

CCA tools now encompass a wide range of frameworks and methodologies, including data provision and visualization, risk and vulnerability assessment, early warning systems, adaptation planning guidance, decision support, and educational or awareness-raising resources[50–55]. These tools help assess climate risks, evaluate adaptation options, improve preparedness in line with disaster-risk-reduction priorities[56], strengthen stakeholder engagement, facilitate knowledge dissemination, support adaptive capacity building, and guide evidence-based policymaking[57–59]. CCA tools play a critical role in bridging the gap between science, policy, and practical

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implementation by synthesising complex and context-specific information like climate projections and socio-economic data into accessible and usable insights for a broad range of stakeholders[60,61]. Such tools are designed to support all the different stages of the adaptation process, from risk assessment to planning, implementation, and monitoring.

As adaptation continues to gain prominence among decision-makers, the demand for systematic tools to guide its planning and implementation has grown significantly. Globally, these tools have evolved from static data portals into a diverse array of platforms ranging from basic data provision systems to complex integrated tools that support comprehensive risk management, scenario analysis, and participatory decision-making[62,63]. Different types of adaptation tools are increasingly being tailored to regional contexts, addressing specific climate vulnerabilities, socio-economic conditions, and stakeholder needs[64–68]. For the Mediterranean, the urgency for adaptation tools is equally, if not more, acute due to the region's heightened vulnerabilities to climate change, including water scarcity, urban heat island effects, flooding, and biodiversity loss[69].

The growing reliance on CCA tools, and their evolution into increasingly sophisticated platforms, does not inherently translate to improved adaptation outcomes[70]. Many of these tools remain overly technical, prioritizing quantitative measurement and heavily relying on technical modelling, while overlooking the socially constructed and politically embedded nature of vulnerability[71]. Tools that overlook underlying power dynamics or fail to incorporate local knowledge, often lead to maladaptation, the misallocation of resources, and the exclusion of marginalized groups[25,72]. A common limitation is that many tools are not sufficiently tailored to decision-making processes in local contexts[73]. They often fail to reflect the institutional realities, resource constraints, and user capacities that shape how such tools are used in practice. As a result, their usability for non-expert users such as local governments, NGOs, and small-scale practitioners remains limited[74,75]. Moreover, many tools require advanced technical skills or have complex interfaces and are often introduced without adequate capacity building support, such as training, institutional assistance, and resources for sustained use. This gap limits their uptake, particularly in settings with limited resources[76,77]. To be effective, adaptation tools must strike a balance between scientific robustness and practical usability, integrating social, economic, environmental, and political considerations into their frameworks. This includes co-developing tools with end users, aligning them with local decision-making processes, and ensuring they support inclusive, sustainable, and context-sensitive adaptation strategies[78–82]. Without addressing these barriers, even the most technically advanced tools may fail to deliver meaningful and lasting adaptation outcomes[83,84].

In light of these challenges and building on a transdisciplinary collaboration within the FutureMed scientific network (a COST Action initiative that bridges climate science, policy, and practice across the Mediterranean), this work presents, to the best of our knowledge, the first systematic, multi-dimensional evaluation of CCA tools relevant to the Mediterranean region. To this end, we search for, compile, categorize, and evaluate 122 global and regional CCA tools, assessing their relevance for the Mediterranean in terms of geographic scale, sectoral focus, intended user group, purpose, potential for scaling and evolution, and where evidence allows, performance in use. Through this analysis, we identify the patterns, strengths, and limitations of the current tool

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landscape. This provides an empirical diagnostic of how the current landscape of tools aligns (or fails to align) with the Mediterranean's specific climatic, ecological, and socio-economic contexts. Theoretically, the study's multi-dimensional approach and regional focus advance understanding of adaptation tools by showing that their limitations often stem from poor alignment with context-specific needs across multiple dimensions. In practice, the resulting inventory and its dataset can serve as a resource for transdisciplinary dialogue and cross-sectoral engagement, among researchers, practitioners, and policy makers seeking to refine or redesign tool functionalities to support adaptive decision-making. The study design, eligibility criteria, and six-phase evaluation workflow are detailed in the Methods section and Supplementary Information (Fig. S1, Tables S1–S3).

Results

User Groups and Sectoral Relevance

Our analysis reveals that CCA tools are designed to serve the needs of multiple targeted user groups, including policymakers, municipal and local governments, educators and academia, researchers, professionals and practitioners from the private sector, communities and non-governmental organizations (NGOs), as well as the general public (Table 1). When considering multi-choice responses, the primary audience targeted is municipal and local government representatives (59%), followed closely by private sector professionals and practitioners (57%) and policymakers (55%) (Fig. 1). When focusing specifically on primary users, municipal and local government representatives remain the top audience (24%), followed closely by both researchers and policymakers (each at 23%). This highlights strong support for policy implementation and top-down practical decision-making at local and regional levels. Conversely, although CCA tools are also accessible to educators, academia, communities, and NGOs, these groups appear to be less frequently targeted users. Notably, when only the primary user group is considered, the overall ranking remains consistent, except within the top four, where researchers' prominence rises slightly to surpass the private sector among the leading targeted user groups.

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Table 1. Heterogeneity of target user groups and their motivations to use CCA tools.

Target user group	Motivation to use the tool
Policymakers (e.g., regulatory bodies, decision-makers)	Setting and implementing climate policy (e.g., *Climate Risk Dashboard*, *1.5º national pathway explorer*)
Municipal/Local governments (urban planners, authorities)	Community adaptation and local planning (e.g., *Urban Adaptation Support Tool*, *ARCH Resilience Measure Inventory*)
Educators/Academia (e.g., professors at different educational degrees)	Integrating climate data, scenarios, and planning tools into educational curricula and research to train future professionals, support climate literacy, and demonstrate real-world applications of adaptation strategies in the classroom (e.g., *Climate Information Portal*, *Global Drought Monitor*, *Copernicus Climate*

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	Change Service through the Copernicus Climate Data Store module).
Researchers (e.g., climate scientists, technicians, professionals)	Research and technical analysis in climate adaptation (e.g., *Clisagri*, *Irish Social Vulnerability to Environmental Hazards Index, CLIMAAX toolbox*)
Private sector professionals and practitioners (e.g. engineers, individuals from industries, businesses, or consulting firms, such as insurance, agriculture, and real estate)	Performing ex-ante climate change impact assessment and risk studies for adaptation strategies and management (e.g., *Building Research Establishment Environmental Assessment Method – BREEAM*, *Data4Risk*)
Communities Organizations/NGOs (e.g., associations, collectives)	Offering awareness-raising perspectives and stimulating community resilience efforts (e.g., *Oxfam's Vulnerability and Risk Assessment*)
General public (e.g., individuals, citizens)	Awareness, personal risk assessment, and learning purposes (e.g., *Sea Level Rise Viewer v 3.0.0*, *MyClimateFuture*)

While many tools are designed for multi-sectoral use with a broad purpose (36%), it is worth highlighting the specific sectors where CCA tools are particularly prominent (Fig. 1). Most applications focus on water resources (38%), urban planning (31%), and agriculture (27%). In contrast, integrated aspects of food security, beyond agricultural production, as well as cultural heritage or waste management receive limited attention.

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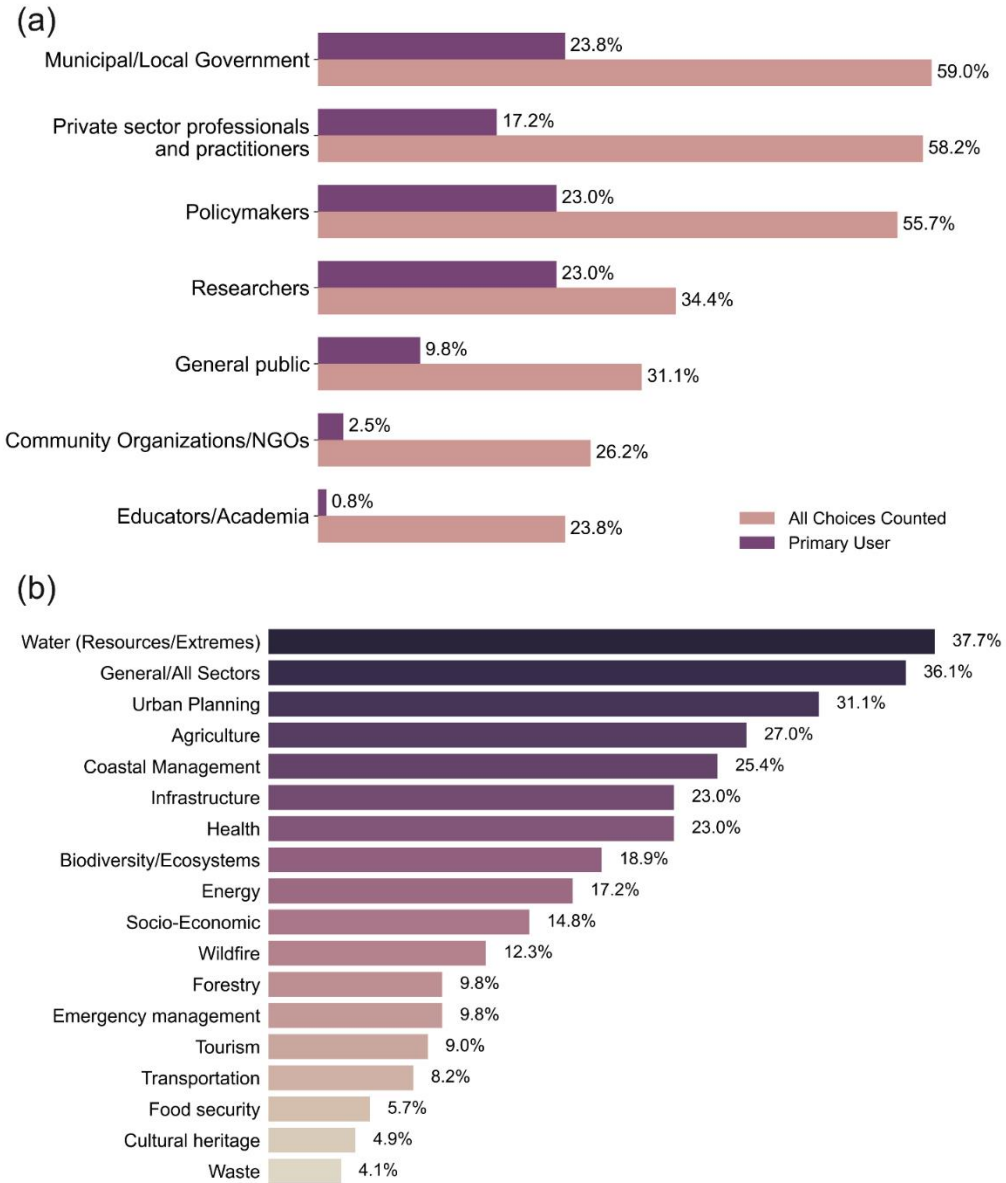


Fig 1. Users and sectors addressed by CCA tools. Intended user groups in (a): light bars show the share of tools that list a group among their intended users (All choices counted); dark bars show the share that designate that group as the primary user. Lower panel (b) shows sectoral focus of CCA tools. Percentages are calculated over n = 122 tools; multiple selections were allowed so totals can exceed 100%.

Tool Types and Functional Distribution

Data Provision and Visualization Tools are the most common categories in the inventory, accounting for 37% of all tools (Fig. 2, top panel). Although targeted primarily at researchers (Fig. 2, bottom panel), these tools facilitate access to climate data, indicators, and processed datasets, often via user-friendly interfaces such as maps or dashboards. This enables them to also support stakeholders in understanding baseline conditions and informing both planning and decision-

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making processes. Outputs from these tools frequently serve as inputs for more advanced instruments, such as Risk and Vulnerability Assessment Tools and Decision Support Systems, bridging the gap between raw data and actionable knowledge. Following this category, three types of tools show relatively balanced distribution. These include Risk and Vulnerability Assessment Tools (18%), Adaptation Planning Guidance and Policy Support Tools (19%), and Decision Support System Tools (17%). Risk and Vulnerability Assessment Tools are used to identify, quantify, and prioritize the risks and vulnerabilities of a system. They are crucial for early-stage adaptation planning as they provide insights into exposure, adaptive capacity, and sensitivity in relation to climate hazards. Adaptation Planning Guidance and Policy Support Tools, on the other hand, assist in structuring adaptation processes by offering frameworks, guidelines, and policy recommendations. They are used to enhance adaptation planning by providing guidance or a framework for the adaptation process, e.g., identifying key steps in stakeholder engagement, monitoring, and evaluation. Decision Support Systems assist users in evaluating options or making decisions based on modelling, ranking, or scenario testing, typically with structured input-output mechanisms. They enable stakeholders to explore and evaluate adaptation options and strategies through scenario analysis, cost-benefit assessments, and multi-criteria decision analysis, thus supporting more transparent and evidence-based decision-making. Early Warning and Resilience Assessment Tools (e.g., Northeast DEWS) are the least represented, accounting for just 2%. These tools are typically designed for specific operational needs, such as issuing hazard alerts. Similarly, Educational and Awareness-Raising Tools (e.g., Climate Resilience Evaluation and Awareness Tool - CREAT), which represent 7% of the total, may be underrepresented due to the informal or cross-cutting nature of the educational content embedded in other types of tools.

As illustrated in the heatmap (Fig. 2), tool design is closely aligned with user group roles. Tools focused on planning and policy, such as Adaptation Planning Guidance and Early Warning Tools, are overwhelmingly targeted at municipal/local governments and policymakers, with over half of them specifically dedicated to these user groups. Decision Support Systems Tools primarily serve institutional actors. In contrast, Risk and Vulnerability Assessment Tools show a more balanced distribution, reaching municipal authorities, the private sector, and to some extent the general public. Meanwhile, Data Provision and Visualization Tools are strongly oriented toward researchers (58%), reflecting the technical expertise required to engage with complex datasets. Community groups, educators, and NGOs remain generally under-targeted across most tool types. Awareness-raising tools (e.g., Climate Resilience Evaluation and Awareness Tool - CREAT) are the most commonly used by communities, while data provision and visualization tools (e.g., Risk Data Hub, Integrated Climate Data Center - ICDC) are the only category in which a few tools explicitly target educators and academia. Nonetheless, as previously noted, other tool types, though primarily designed for institutional or professional users, may also be effectively applied in higher education settings.

Some tools offer different functionalities tailored to the needs of different user groups. For example, the *Digital Climate Atlas of Serbia,* which enables the monitoring of a large number of climate variables and serves as a foundational resource for all climate-related initiatives, or *Romania's Climate Change Adaptation Platform* (RO-ADAPT), a geoportal that provides a virtual

working environment with access to diverse climate datasets, are both classified as Data Provision and Visualization Tools. These tools offer differential access: general users can view climate data and download visual outputs (e.g., images or files), while researchers and academic users have access to advanced features, such as downloading NetCDF files for more in-depth analysis. Policymakers, municipal or local government representatives, professionals, and practitioners from the private sector, as well as the general public, can also interact with and use the climate data according to their needs via the tools' online interface. Other tools are more targeted in scope. For example, *BREEAM* is a science-based sustainable building certification system that offers actionable insights to local communities, and *icclim* is a Python library specifically designed for researchers to advance climate impact studies.

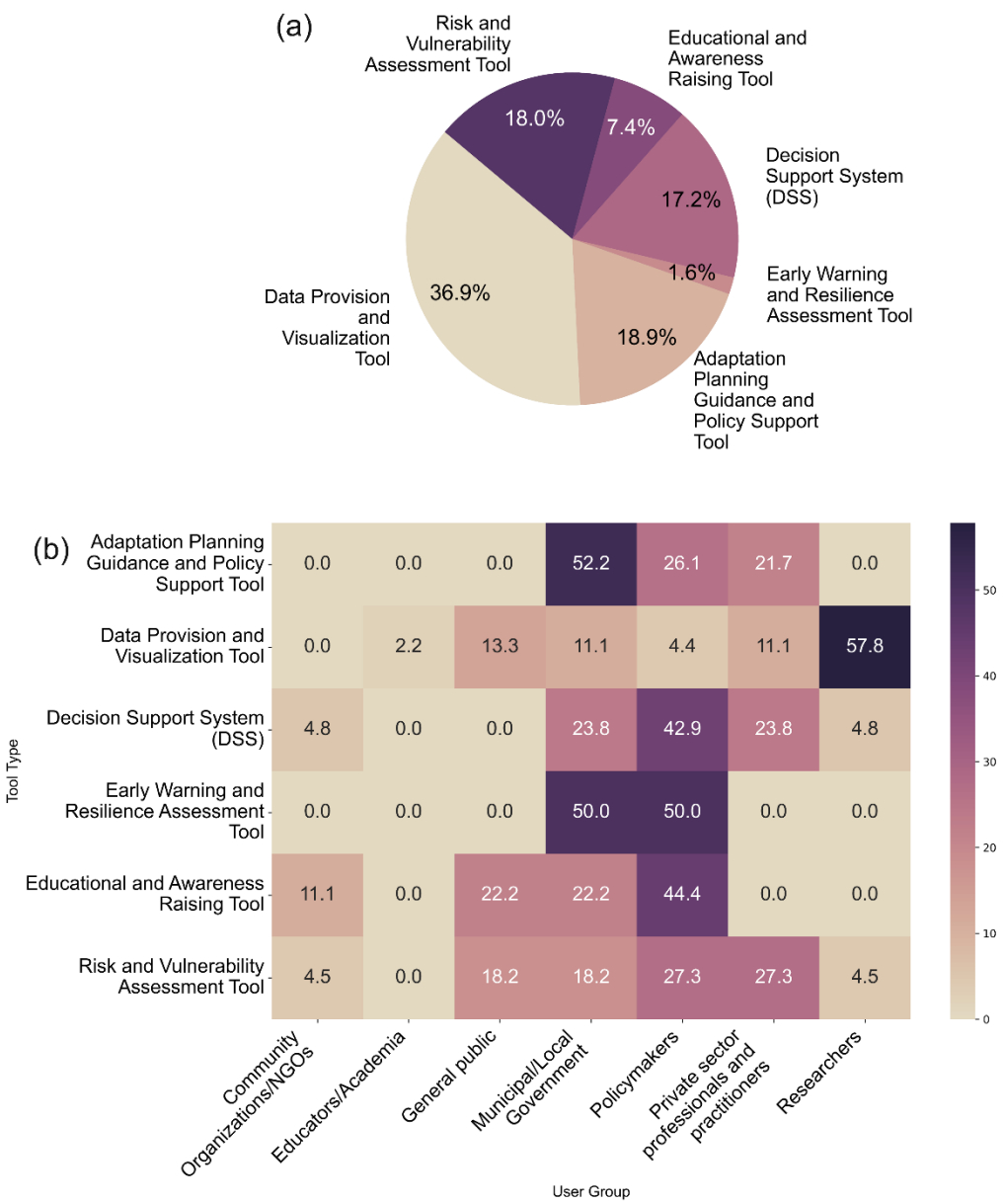


Fig 2. Types of CCA tools and their intended users. Top (a): Distribution of tools by primary intended use (%, n = 122). Tools may support several objectives but are classified here by the main purpose stated in their documentation. Bottom (b): Association between tool type (rows) and intended user groups (columns). Cell values give the percentage of tools within each type that target each group (row-normalised; totals per row = 100%); a tool may target multiple groups.

Temporal and Spatial Scales

CCA tools can be grouped by whether they spatially follow political (reflecting administrative and governance levels) or physical (such as ecological, hydrological, or landscape-based units) boundaries. Tools built around political boundaries are by far the most common (39%) (Fig. 3), and tend to operate across multiple geographical scales, each receiving similar levels of interest (approximately 20%). This indicates their greater potential flexibility for application across various management and decision-making contexts, from local to international levels, though whether this design flexibility translates into actual multi-scale use was beyond the scope of this assessment. Most tools align with governance structures, thereby supporting decision-making processes at local, national, and international scales. In contrast, tools based on physical boundaries are used to a more limited extent. Attention is relatively balanced between landscape-based and urban/rural dynamics (about 7% each), while those utilizing ecosystem or watershed boundaries remain notably underrepresented (<1%). These findings highlight a clear gap in how CCA tools integrate to administrative rather than to biophysically meaningful boundaries such as catchments, ecosystems, and landscape units. This pattern is likely reinforced by the structure of research funding itself since European and national calls typically require multi-country consortia organized along administrative boundaries, and reporting obligations are tied to governance units, which naturally orient tool development towards political rather than biophysical scales.

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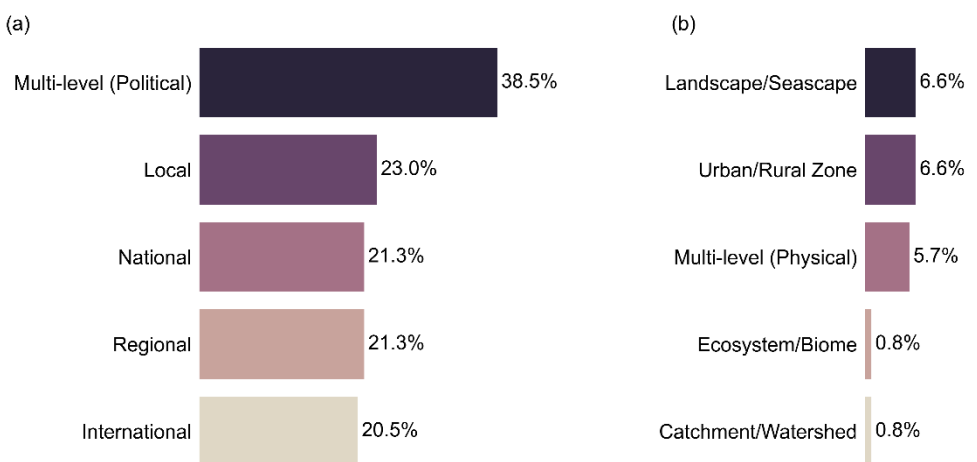


Fig 3. Spatial scales used by CCA tools. (a) Administrative/political scales reported by tools (local, regional, national, international, multi-level [political]). (b) Biophysical scales

(landscape/seascape, urban/rural zone, multi-level [physical], ecosystem/biome, catchment/watershed). Percentages on bars indicate the proportion of tools stating applicability at each scale (based on tool documentation; n = 122). Multiple selections were allowed per tool, so totals can exceed 100%. Note: the horizontal axis range (bar scale) differs between panels.

Temporal scale and resolution are also important aspects for the application of CCA tools. The temporal scale refers to the intended planning timeframe, ranging from short-term decision-making (e.g., days or months ahead) to long-term adaptation strategies (e.g., multidecadal projections). Temporal resolution is about the granularity of data or processes represented in outputs (e.g., daily, monthly, or annually). As shown in Fig. 4, long-term scales, including decadal or multi-decadal contexts, are the most common, present in nearly half of the tools (48%), followed by past and present scenarios (36%), and a combination of multiple time scales (29%). This distribution aligns with the findings for temporal resolution, where three out of four tools are based on multi-year or long-term statistical outputs. However, certain tools categorised under long-term temporal scales (e.g. CDS and Climate4Impact) also provide outputs at shorter time intervals (e.g. daily or monthly). These outputs are crucial for operational needs in sectors such as agriculture and forestry that require high-frequency data to monitor environmental conditions, detect anomalies and develop sector-specific indicators. However, while these sectors may not primarily rely on long-term projections, the availability of high-resolution data across extended timeframes supports robust trend analyses and long-term planning, for example, to develop sector-specific indicators (e.g., *CDS*, *Climate4Impact*). In these cases, “seasonal” does not imply medium-term planning but rather a type of output resolution used within long-term planning frameworks. Furthermore, there are tools (e.g., *Oxfam's Vulnerability and Risk Assessment Toolkit*, *Pathways2Resilience Climate Toolbox*, *ARCH Resilience Measure Inventory*) that do not focus on a specific temporal resolution or produce outputs that align with the defined temporal resolution. Instead, they are designed for strategic planning (e.g., adaptation planning, adaptation collaborative toolkit, Decision Support Systems) or community-led assessments using qualitative methods. As a result, the option ‘Not Specified’ was applied to these tools, since conventional categories like ‘monthly’ or ‘annual’ do not accurately reflect how the tools function.

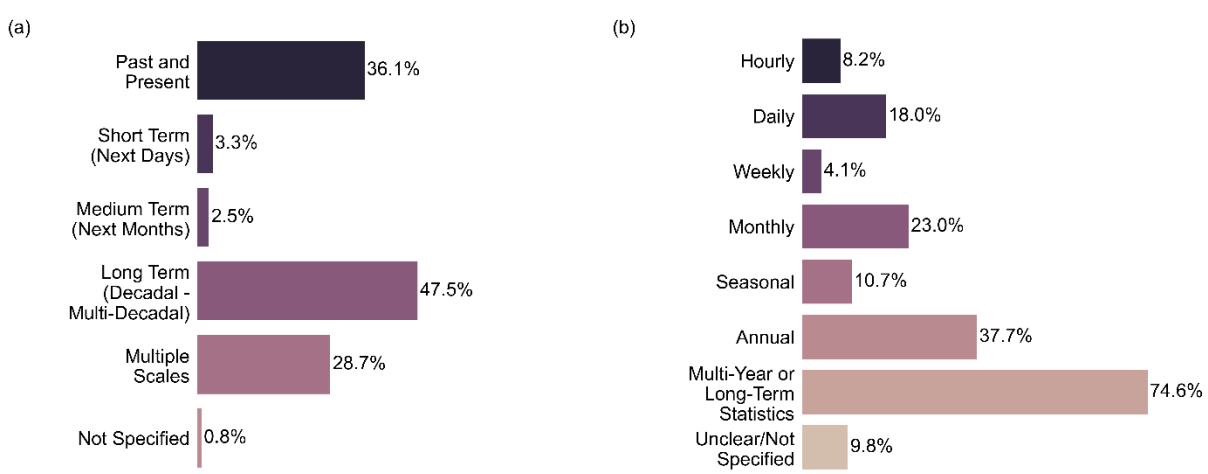


Fig 4. CCA tools’ temporal scale and time resolution features. (a) Temporal scale addressed by each tool (past/present; short term; medium term; long term; multiple scales; not specified).

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(b) Time resolution of inputs/outputs (hourly, daily, weekly, monthly, seasonal, annual, multi-year/long-term statistics, unclear/not specified). Percentages on bars indicate the proportion of tools reporting each option (based on tool documentation; n = 122). Multiple selections were allowed per tool, so totals can exceed 100%. Note: the horizontal axis range (bar scale) differs between panels.

Tool Methodologies and Data Utilization

The inventory of CCA tools reflects a rich methodological diversity, shaped by different disciplinary origins, user needs, and intended applications, and also displays a varied preference for different types of data (Table 2). More than half of the tools (52%) rely on quantitative data, with secondary, aggregated data (47%) used more frequently than primary, detailed data (6%). This suggests that many tools favour the use of pre-processed datasets, such as climate projections (e.g., *CDS*, *Climate4Impact*), socio-economic metrics (e.g., *Shared Socioeconomic Pathways (SSP) Explorer*, *Urban Adaptation Support Tool*), or hydrological outputs (e.g., SMHI HYFO, Global Drought Monitor, Derris). These are frequently used to support national or regional climate services (e.g., *Digital Climate Atlas of Serbia*, *SMHI Aqua*, *Klimaticka zmena*, *Thermal Assessment Tool*) as well as international platforms (e.g., *Global Drought Monitor*, *Data4Risk*). Interestingly, more than one-third of the tools (37%) rely on mixed data –data-quantitative and qualitative-and– are characterised by flexible source and granularity. This offers greater flexibility to support varying user needs and resource capacities. In contrast, a smaller share of tools (11%) is based solely on qualitative data, whether primary or aggregated. These tools utilize original numerical data collected through methods like field measurements or surveys (e.g., *Hypewebb*, *SMHI HYFO*), or gather descriptive data directly from stakeholders through interviews or workshops (e.g., *Tribal Climate Change Adaptation Planning Toolkit*).

Many tools can employ multiple approaches, and most of them rely (or have a component) on scenario-based, predictive, and quantitative methods (57%). These typically integrate future climate projections to assess potential impacts and inform adaptation planning (e.g., BRACE framework). This suggests a primary focus on anticipating climate-related risks and supporting evidence-based decision-making, particularly for developing forward-looking strategies. Tools like *Climate4Impact* exemplify this approach by offering access to climate model data and visualization features tailored to various user needs. Likewise, more than half of the tools (51%) use spatial and geographic analysis, reflecting the importance of place-based information for gathering context-specific outputs that are critical for targeted climate adaptation measures.

Table 2. Output modality, granularity and analytical approaches of CCA tools. The “Type of data” section describes the modality and granularity of outputs (quantitative vs qualitative; detailed vs aggregated), while the “Approach and analysis” section lists the embedded analytical methods. Full details are in the Supplementary Information (Criteria for Tool Systematization).

Type of Data			
Data modality	Source/granularity	Use (%)	Use (nº of tools)
Quantitative	Primary (detailed)	5.7	7

	Secondary (aggregated)	46.7	57
Qualitative	Primary (detailed)	3.3	4
	Secondary (aggregated)	7.4	9
Quantitative & qualitative (both)	-	36.9	45
Approach and analysis			
Type of approach & analysis	Description	Use (%)	Use (nº of tools)
Scenario, predictive & quantitative	Models/data to project futures and compare options	57.4	70
Spatial & geographic	Mapping and spatial pattern analysis	50.8	62
Frameworks & structured processes	Stepwise guidance that structures decisions	28.7	35
Participatory, stakeholder-engagement & community-led	Co-production with stakeholders/communities	17.2	21
Policy & economic	Policy/economic appraisal and trade-off analysis	14.8	18
Note: In "type of approach and analysis", multiple options were allowed, and the percentages represent the proportion of climate tools.			

Outputs, Customization, and Usability

The most frequent outputs among CCA tools are maps and visualizations (62%), reinforcing a continued need for spatially explicit, easily interpretable information. In comparison, nearly half (49%) of the tools provide reports and guidelines (Fig. 5a). Tools that generate maps or other visualizations, commonly also provide access to the raw/processed data based on which visualizations were made. This indicates that many platforms serve as climate information hubs, providing users with access to downloadable data and knowledge (e.g., the web portal of the *Integrated Climate Data Center,* ICDC, at the University of Hamburg).

Reports (e.g., Northeast DEWS, European Forest Fire Information System - EFFIS, Climate Adaptation Knowledge Exchange - CAKE), frameworks (e.g., *Urban Adaptation Support Tool*) and assessments (e.g., *Climate Risk Dashboard* provided by the PROVIDE and CLIMAAX projects) illustrate how tools can be used to conduct sectoral analysis for various climate risks, typically utilizing uniform formats or templates that can be adapted to multiple socio-economic sectors. In the same vein, tools serve as foundational resources, providing datasets (e.g., the *European Forest Fire Information System*, EFFIS), climate indices (e.g., the Python package *Climdex-kit* for multi-scenario calculation, publishing, and analysis of indices from 3D time-series of climate projections, or the *IMPACT2C web-atlas* to summarise in maps and texts the impact of global 2°C warming on different sectors), and general-purpose outputs that can be tailored to meet the specific needs of different sectors (e.g. Adaptation Workbook, Urban Adaptation Support Tool).

CCA tools vary in terms of ease of use (Fig. 5b). The majority (64%) are designed to be "user-friendly" and intuitive for a broad audience with minimal technical background (e.g., *Climate-ADAPT*, *Climate4Impact*). For instance, *My Climate Future* communicates potential climate

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impacts at different levels of global warming in a clear and engaging way. Another example is the *Climate Adaptation App*, which targets urban designers, engineers, and other professionals, offering very user-friendly navigation on the platform and a comprehensive user guide to support practical decision-making. It suggests feasible adaptation measures tailored to specific local conditions and user-defined goals, such as preparing urban developments in floodplains for river flooding. These tools often include clear instructions, straightforward interfaces, and helpful support materials, tutorials, or user manuals.

Language options are limited (Fig. 5c). Nearly all tools are available in English (97.5%), while availability declines sharply for other languages: Spanish and French (each 11.5%), Italian (8.2%), German (6.6%), Portuguese (4.9%), Arabic (3.3%), and Russian, Romanian and Swedish (each 2.5%). Only a small subset provides more than one non-English option, which constrains uptake among users who operate primarily in national languages.

Approximately one-third of the CCA tools require some technical or scientific knowledge to use (Fig. 5d), (e.g., the *CLIMAAX* toolbox). These tools are better suited for researchers, professionals, or technical users rather than the general public or municipal and regional governments. Users need to be comfortable with navigating data interfaces, choosing among options given by the tool, and interpreting outputs. In this regard, a small share (7%) of tools is highly complex, targeting experts such as climate scientists, engineers, or risk analysts. They typically require in-depth domain knowledge to operate effectively and interpret outputs (e.g., CLIMAAX toolbox). However, this categorization might be somewhat subjective and may vary depending on the background and expertise of individuals conducting the evaluation. What is perceived as "easy to use" by someone familiar with climate data or tool interfaces might present barriers to stakeholders with limited experience. Additionally, variability in documentation availability, language options, or platform stability may influence the perceived accessibility. Accordingly, the usability classifications reported here reflect the collective co-authors' expert assessment of design features and documentation rather than end-user experience, and should be interpreted as indicative of intended accessibility rather than confirmed ease of use in practice.

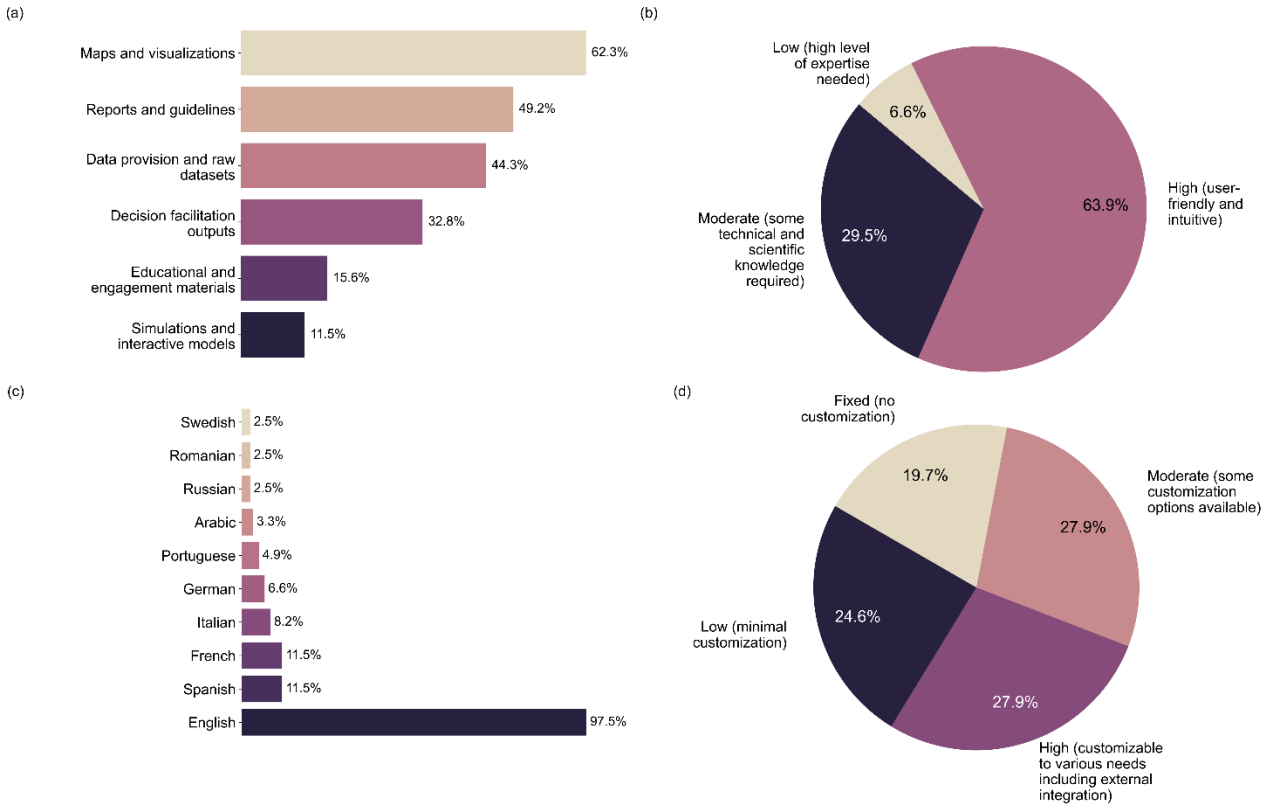


Fig 5. Overview of characteristics of CCA tools. (a) Output typology (e.g., maps/visualizations, reports/guidelines, data provision, decision-facilitation outputs, educational/engagement materials, simulations/interactive models), (b) Accessibility and usability levels (high, moderate, low), (c) Multi-language support (top 10 languages represented), and (d) Customization options (high, moderate, low, fixed). Note: Multiple selections were allowed for (a) and (c), and the percentages indicate the proportion of tools (*n* = 122) offering each feature. Definitions follow the coding schema in the Supplementary (Criteria for Tool Systematization).

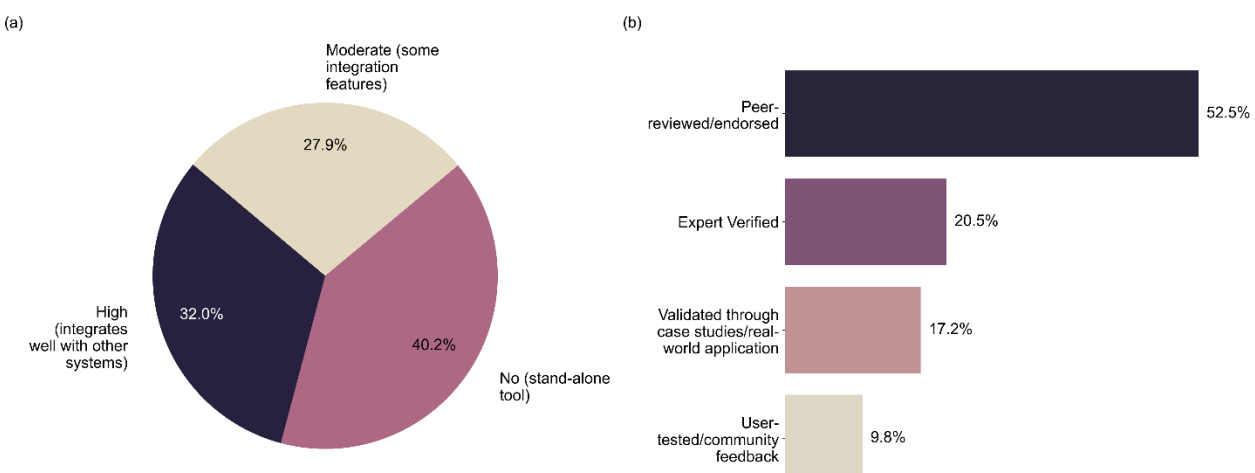
Integration, Validation, and Reliability

CCA tools also vary in their potential for easy integration with other tools. About 40% are stand-alone tools that operate independently, without connecting to external systems or data sources, which means avoiding data exchange or integration (Fig. 6a). However, almost one third of the tools (32%) can easily integrate with a wide range of external systems, datasets, and other tools, being compatible with commonly used platforms. Some tools that fall into this "high integration" category (customizable to various needs including external integration) include platforms such as *CLIMAAX* and *climate4R,* which offer flexibility in data processing, access to APIs, support for multiple output formats, and integration into coding environments or external visualization tools. These features make them suitable for advanced workflows, such as automated analyses, dashboard creation, or integration into decision-support systems. However, integration capability is often closely linked to the intended user group: tools for technical users and researchers tend to offer more interoperability, but also tend to require more technical expertise. In contrast, tools targeted at the general public are more often stand-alone and focused on ease of use rather than

customization. It should be noted that the integration capability reported here reflects design features and documented specifications. Whether these capabilities translate into actual integration in practice and the institutional, governance, and resourcing barriers that may prevent this, was not assessed in this study and warrants dedicated investigation. For local and regional governments, policymakers, or the general public, integration may be more relevant in terms of how easily a tool connects with existing planning platforms or operational workflows without requiring high technical expertise. For example, tools like *Hotel Resilient* offer structured, sector-specific place-based risk assessments and adaptation planning aligned with local needs. Similarly, the *Adaptation Support Tool on Climate-ADAPT* provides step-by-step guidance for policymakers, allowing operational integration into institutional ordinary decision-making processes.

To assess validation and reliability, the analysis examined how extensively each tool has been tested, reviewed, or endorsed for use. Although some tools may fall into more than one category of validation, the analysis was based on their primary or most prominently stated validation method. Results highlight that more than half of the investigated CCA tools (52%) have undergone formal peer review or received endorsements from reputable institutions, such as academic bodies, governmental organizations, or international agencies (Fig. 6b). This level of validation reflects a high degree of credibility, as these tools have been evaluated using well-established scientific frameworks to ensure robustness, methodological soundness and policy relevance. A smaller but notable proportion (17%) has been validated through case studies or real-world applications, demonstrating practical utility and offering empirical evidence of their relevance and performance (e.g., *Climate and Clean Air Coalition*, *Climate and Disaster Risk Screening Tool*). Approximately 20% of tools have been verified by domain experts or practitioners, despite not necessarily undergone formal peer review, while tools primarily validated through user testing and community feedback account for 10% of the inventory. *IMPETUS HIPS* or climate-indices available on Python projects to provide a geographical and temporal overview of the severity of precipitation and temperature anomalies, useful for climate monitoring, are indicative examples.

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Fig 6. Integration capability and validation status of CCA tools. (a) Integration capabilities as share of tools classified as No (stand-alone), Moderate (some integration features), or High (readily integrates with other systems via standard formats/APIs). (b) Validation/Reliability of CCA tools as share of tools reporting Peer-reviewed/endorsed, Expert verified, Validated through case studies/real-world application, or User-tested/community feedback. Note: Percentages are calculated over n = 122 tools. Single selection was allowed per tool in both panels. Definitions follow the Supplementary Methods (Criteria for Tool Systematization).

Cost and Maintenance

According to the analysis, cost is generally not a barrier to accessing climate change adaptation (CCA) tools, with 89% of tools being free to use. This widespread availability aligns with the public-good nature of climate adaptation and the commitment of many institutions and projects to support broad access, particularly for resource-limited users such as local governments or NGOs. However, the small proportion of tools offering tiered pricing (7%) or subscription models (4%) suggests that some tools may have advanced features or support services gated behind a paywall. These may include premium analytics, priority technical support, or additional datasets, for example, *CatNet* or *Envision Sustainable Infrastructure Framework*, which provides differentiated access or pricing tiers based on user type, such as individual professionals, academic institutions, or private-sector organizations. The negligible share of one-time purchase models (1%) implies that commercial software is rare in this domain.

The majority of the evaluated tools (71%) are actively maintained, either with full technical support or with limited support (Table 3). A substantial portion of tools (42%) receive regular updates along with full technical support, indicating active development and user responsiveness, while nearly a third (30%) are regularly updated but offer only limited support, such as basic documentation or delayed help-desk responses. A notable refinement during the inventory was the introduction of a new category, ‘Static’, including two subcategories: 1) tools with limited support (6%), which are no longer actively maintained but still provide users with support mechanisms like documentation, archived email contacts, or functioning portals and 2) tools initially well-supported during their project lifecycle but became static post-funding. The first subcategory captures platforms developed under fixed-term projects or funding phases, such as national platforms like the Digital Climate Atlas of Serbia. In contrast, the second subcategory represents tools, like *Adapt2Clima* or the *Climate Vulnerability Monitor,* that technically are still operational, but may no longer evolve, offering no new features, datasets, or updates.

Table 3. Maintenance and Support of CCA tools.

Type of process	Use (%)
Regular updates	71.3
- *With full technical support*	41.8
- *With limited technical support*	29.5
Occasional updates with community support	11.5
Static	16.4
- *With limited technical support*	5.7

- No updates or support	10.7
In development	0.8

Note: Only one option was allowed to be selected

Not surprisingly, tools funded through subscriptions or tiered pricing are significantly more likely to offer consistent maintenance and comprehensive user support (Fig. 7). In contrast, one-time purchase tools often lack post-sale support, reflecting a limited commitment to long-term upkeep. Free tools vary considerably, with some matching or exceeding the support levels of paid tools, while others rely on volunteer or community-based support. These numbers suggest that for a relevant percentage of tools, which are often freely available and originate from public research projects, the uncertainty of funding beyond the project lifetime can impact the availability of technical support or regular updates. This concern is compounded by a mismatch between funder expectations and funding provisions: for instance, the European Commission expects exploitation of R&I project results for up to four years beyond project end, yet dedicated funding for tool maintenance, technical support, and data updates during this period is rarely provided[80].

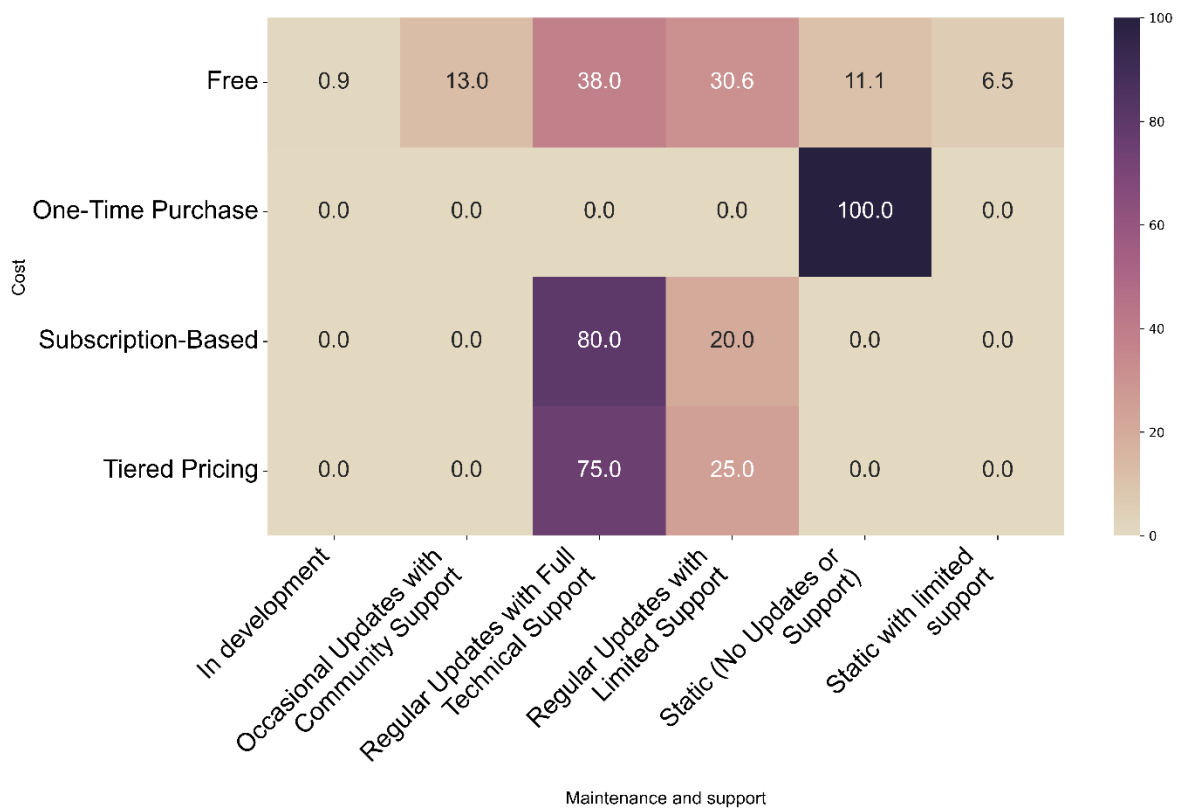


Fig 7. Cost versus maintenance and support for CCA tools. Heat map illustrating the relationship between the cost of a CCA tool and the level of maintenance and support offered (%). Definitions follow the coding schema in the Supplementary Information (Criteria for Tool Systematization).

The nexus between the type of tool and the user group can influence the relation between cost structure and the intended user base (Fig. 8). Tools designed for wide public or academic use

tend to be free or flexibly priced. In contrast, those targeting decision-makers or professional users are more likely to involve commercial pricing models that support sustained service provision and technical maintenance. One-Time Purchase Tools are exclusively aligned with policymakers and decision-makers, comprising 100% of the tools in that cost category. An example is the *Youth Engagement in Science and Technology Resilience* (YES-TR), a specialized resilience-building tool developed for structured decision-making processes in policy and governance contexts. Subscription-based tools are primarily directed at private sector professionals and practitioners (60%) and municipal/local governments (40%). They also offer customization according to the users' needs. One such example is *SMHI Aqua*, a hydro-climatic service that models freshwater availability and supports operational planning by local authorities and water utilities through a combination of one-time implementation and annual subscription fees.



Fig 8. Cost by primary user group for CCA tools. Heat map with cost categories and primary user groups showing distribution of CCA tools' Cost across primary User Group (%).

Geographical distribution and focus on the Mediterranean region

The geographical scope of the CCA tools shows a strong emphasis on globally applicable resources, with over half (52%) of the tools designed for use in multiple regions worldwide (e.g., CLIMWAT) (Fig. 9a). Despite the high vulnerability of the Mediterranean region to the impacts of climate change, there seems to be a limited number of tools (10 out of 122; 8% only) developed explicitly for it. However, many globally and Europe-oriented tools include the Mediterranean

region, with 65% (79 out of 122) offering some level of coverage. This suggests that although the Mediterranean may not always be the primary focus, it is often covered. That is, when entailing the internal distribution of the Mediterranean perspective, it has been observed that most tools (70%) (Fig. 9b) adopt a holistic vision of the Mediterranean, whereas less than a third (26%) focus on northern Mediterranean countries, such as *ADAPT2CLIMA*, *Città Clima* or *ARCH DSS*.

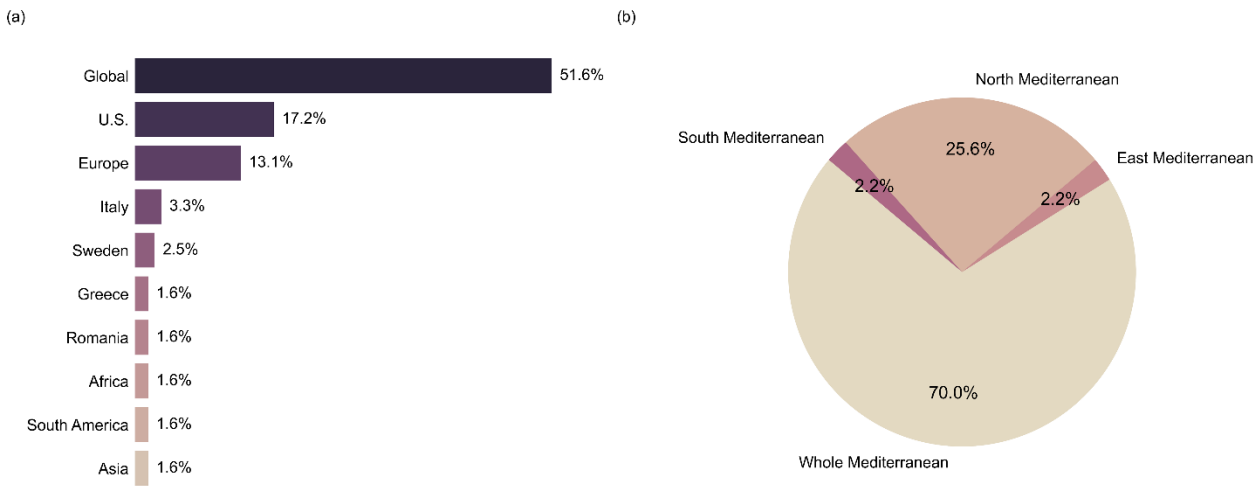


Fig 9. Top ten primary geographical area coverage by CCA tools. (a) Top ten primary geographic areas of applicability as stated in tool documentation (share of all tools; n = 122). (b) For the subset of tools with Mediterranean coverage (i.e. n = 89), distribution across sub-regions (Whole, North, East, South Mediterranean); percentages are within this subset and sum to 100%. Note: Tools under the 'Europe' category have been accounted for in 'North Mediterranean'.

Discussion

The inventory assembled in this study spans tools of diverse geographic origin and scope, ranging from global platforms to national services, each assessed for its relevance to the Mediterranean context. This work reveals that, although many tools provide access to high-quality data, advanced projections, and technical guidance, their design often fails to reflect the region's ecological complexity, fragmented governance, and diverse stakeholder needs. While the Mediterranean serves as our analytical lens, these limitations are likely to extend to other climate-vulnerable regions. In the Mediterranean, where climate impacts are intensifying and adaptation needs are urgent, effective tools for robust adaptation planning are crucial.

Our evaluation shows that current tools have significant potential. They can offer high-quality climate data, inform planning in key sectors such as water, agriculture, energy, and urban development, and help bridge science and policy[12,14,53]. However, persistent shortcomings in design, inclusivity, and validation constrain their uptake and potential impact.

These shortcomings start with the way tools are tailored. Most tools are designed for municipal and local governments, private sector actors, and policymakers. Communities, NGOs, and educators, who plays a vital role in bottom-up adaptation by improving local relevance, legitimacy, and long-term effectiveness of actions[85], are significantly underrepresented. Participatory

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approaches or co-development processes are rare, and when engagement is promoted, it often amounts to symbolic consultation with little influence on tool design or outputs. Notable exceptions include tools such as the Local Climate Adaptation Tool (LCAT), which was co-designed with over 50 local authority areas and Oxfam's VRA, which uses structured participatory workshops to enable communities to define risks and priorities. SMHI-Aqua and HYFO are also tools developed after extensive end-user engagement. Although rare, these examples demonstrate that co-designed tools can achieve stronger uptake and greater local relevance[86]. Recent studies further show that the effectiveness of adaptation measures is closely linked to meaningful citizen engagement and co-production[87–89].

Despite the Mediterranean's status as a climate-change hotspot, only 8% (n = 10 CCA tools) of tools are explicitly designed for the region (Fig. 9a). Although many global or European platforms (65%) include Mediterranean coverage, few are tailored to its sub-regional realities. Most tools structure spatial information around administrative borders rather than ecological or hydrological units like watersheds, even though ecosystems, water resources, and coastal systems transcend administrative divisions. This mismatch hampers the tools' ability to support integrated, cross-sector planning in agriculture, water management, and urban development[90]. When ecological diversity is not accounted for, tools lose their practical value for local decision-making, leading to inefficient resource allocation, weakened resilience, and poorly targeted risk responses[91,92].

Another conceptual gap lies in the emphasis on single hazards. Few tools capture the interactions between hazards or the cascading dynamics that characterize Mediterranean climate risks. As Sfetsos *et al*.[93] note, compounded multi-hazard extremes show a high degree of geographical variation in their projected occurrence, intensity, and duration, underscoring the limits of single-hazard approaches for estimating exposure or guiding planning. Similarly, most tools do not distinguish clearly between climate and non-climatic drivers, making it harder for decision-makers to interpret risks. Effective systemic adaptation requires accounting for interdependent hazards and compounding pressures, as well as cross-sectoral trade-offs and synergies among adaptation measures. For instance, how water management interventions interact with agricultural productivity, tourism water demand, or energy demand. This is particularly relevant given the EU Adaptation Strategy's call for systemic adaptation[94]. While some tools (such as IMPETUS HIPS) address multiple sectors or offer partial cross-sectoral functionality, none explicitly captures the full interdependencies, cascading effects, and feedback loops that systemic adaptation demands.

Methodologically, many CCA tools are designed with a high degree of technical complexity and rely heavily on quantitative modelling, statistical outputs, and standardized indicators. Quantitative methods are indispensable for quantifying magnitudes, mapping exposure, and comparing scenarios, but they cannot on their own capture the full breadth of risks, uncertainties, vulnerabilities, and adaptation dynamics as they are context-dependent and socially constructed[95]. Qualitative methods are essential for retracing the mechanisms through which hazards become risks, impacts are perceived and vulnerabilities persist, and adaptation measures succeed or fail, illuminating the *why* and *how* behind the numbers[96]. To guide

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adaptation as it coevolves within socio-environmental systems demands approaches that account for the mutual shaping of environmental and societal dynamics and deliberately integrate multiple methods to grapple with this complexity[97].

The predominance of quantitative, expert-oriented tools in our inventory is not merely a technical design choice. It reflects broader political economy dynamics that shape what kinds of knowledge are valued, produced, and rewarded. Funding structures, particularly competitive research calls, tend to favour quantitative, model-heavy, and often technocratic outputs that can be more easily demonstrated, measured, and reported as deliverables. By contrast, co-producing tools with local actors and integrating local knowledge through iterative design and sustained engagement are harder to fund and slower to yield measurable results[70,98]. As Boon *et al.*[99] observe, climate services deemed successful by developers are not necessarily perceived as useful by decision-makers, precisely because the criteria for success often diverge from the needs and realities of practice. This misalignment between what is funded, what is built, and what is needed echoes the broader science–practice gap in adaptation planning[72,100], where tools proliferate without systematic attention to whether they are adopted, embedded in governance routines, or effective at informing decisions[77].

Usability and access barriers further constrain adoption. Although approximately 64% of tools are described by experts as user-friendly based on their documentation and interface design, many still require advanced technical expertise or scientific knowledge, which can exclude local practitioners, NGOs, and smaller institutions with limited resources. Insufficient documentation, limited availability in local languages, and design choices that implicitly prioritize expert users further reinforce these barriers. Such usability constraints limit the uptake of tools across different actors and governance levels, while also obstructing collaborative adaptation planning. More fundamentally, barriers to access shape who can engage with adaptation processes, whose knowledge is recognized, who benefits, and who is systematically excluded from adaptation initiatives[101]. When tools underrepresent diverse knowledge systems and fail to integrate local expertise, they risk excluding those most vulnerable and most knowledgeable about site-specific conditions[27,101–104]. This exclusion not only undermines equity but also contributes to maladaptation, inefficient resource allocation, and the reinforcement of existing inequalities[25,72].

Long-term sustainability and reliability present another limitation. Although nearly 89% are freely available, many rely on short-term project-based funding, creating uncertainty about maintenance and data updates. While 71% of tools are regularly updated, about 16% remain static, heightening the risk of obsolescence as climate risks evolve and understanding of adaptation, social vulnerability, and the political economy dimensions of risk continues to advance. Validation practices also vary widely, with roughly half of the tools being peer-reviewed or institutionally endorsed, but fewer than 10% having undergone field testing or user-based validation in Mediterranean contexts. Echoing Bamzai-Dodson *et al.*[105], this limited validation reduces confidence in outputs and hampers their use in adaptation planning, particularly in sectors such as water security, disaster risk reduction, and agriculture where decisions must be informed by robust and contextually grounded evidence. It is therefore legitimate to ask whether many

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adaptation tools are being built for being used or simply to be developed, and whether their primary purpose is to demonstrate technical capacity rather than to deliver sustainable solutions in real contexts.

Research funding structures reinforce this emphasis on technical performance by rewarding novelty and encouraging the development of new tools as deliverables in project proposals, rather than the consolidation, improvement, or sustained maintenance of existing ones. The digital humanities literature points to a similar proliferation of tools that are highly sophisticated in design but poorly adopted or eventually abandoned[106]. The result is what some scholars describe as *a cemetery of tools,* platforms launched with promise but left underused, under-maintained, or eventually abandoned once project funding ends. This dynamic also affects user trust. When practitioners observe that tools are frequently superseded or discontinued, they may hesitate to adopt new ones, either relying on familiar tools regardless of their limitations or postponing adoption in anticipation of the next generation[100].

Taken together, the patterns documented across tool design, usability, validation, and sustainability are not isolated shortcomings. Rather, they reflect broader barriers to effective adaptation long identified in the literature, including institutional fragmentation, mismatch between administrative boundaries and ecological realities, inadequate stakeholder engagement, and short-term planning[42,70,107]. Our analysis therefore suggests that the current tool ecosystem, rather than helping to overcome barriers to adaptation, largely reproduces them in digital form. While general critiques that adaptation tools do not meet user needs are widely recognised, our analysis advances the debate by systematically characterising this misalignment for the Mediterranean. Here, the regional focus does not simply provide the setting for the analysis, it enables the diagnosis. By quantifying shortcomings across spatial framing, user inclusivity, linguistic accessibility, validation and long-term sustainability, the Mediterranean frame of analysis reveals discrepancies between what adaptation tools are designed to do and what adaptation in the region actually requires. Such regional lens thereby moves the discussion from theoretical observations to practical guidance on where and how tool ecosystems can be improved. Our argument underscores that these challenges cannot solely be addressed through better interface design or expanded datasets. Improving the tool landscape also requires confronting the governance and funding structures that shape what tools are built, for whom, and to what end. The potential of adaptation tools can only be realised when design shifts from data-centric to user-centred approaches[72,108,109], and when evaluation moves away from assessing what tools can do in principle towards documenting what they achieve in practice[105].

Finally, a limitation of this assessment is that usability, accessibility, and integration capability were evaluated by expert reviewers on the basis of tool documentation and functionality, rather than through direct engagement with end-users. Future work should therefore complement this supply-side evaluation with demand-side perspective to assess whether tools are adopted, how they perform in real decision-making contexts, and what barriers users encounter in practice[110]. Evaluations of adaptation support tools confirm that user involvement in design and iterative feedback loops is among the strongest predictors of actual uptake and decision influence[108,109].

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Conclusion and Recommendations

This article presents, to the best of our knowledge, the first comprehensive and systematic evaluation of CCA tools relevant to the Mediterranean region. The analysis shows that, while the current tool landscape is broad and often technically sophisticated, it remains persistently misaligned with the region's ecological and societal realities. Many tools are freely available and potentially useful for informing planning, yet they are not calibrated to Mediterranean contexts, marked by uneven usability, often restricted to English, and rarely co-developed with those most affected by climate impacts. As a result, their uptake beyond expert institutions remains limited, with negative consequences for learning across governance levels and for their capacity to inform systemic and equitable adaptation.

More broadly, the tool landscape offers an empirical window into the science–practice gap in adaptation. The very instruments that are meant to bridge this gap currently reflect, rather than resolve, its underlying structural causes. Because the inventory was assembled broadly and examined through a Mediterranean frame of analysis, the patterns identified here likely extend to other climate-vulnerable regions. At the same time, some gaps revealed by the study are distinctively Mediterranean, including fragmented cross-border governance, the near-absence of catchment-based tools, and the dominance of English-language interfaces despite a multilingual user base. The Mediterranean's combination of heterogeneous institutional settings, ecological diversity alongside acute and varied climate risks makes it a useful testing ground for developing, evaluation, and refining tools, before adapting them to other contexts[111].

The way forward is not to proliferate more tools, but to rethink how tools are conceived, governed, and used. This requires a shift from data-centric to user- and context-centred design. Tools should be co-created with communities and local actors so that local knowledge, languages, needs, and constraints are embedded in their framing, interfaces, and outputs. Participation must be genuine rather than symbolic, redistributing influence and recognizing the power dynamics that determine whose vulnerabilities are addressed and whose voices are heard.

Next-generation tools should move beyond static platforms and data-heavy models. They need to be open, modular, and able to fit into day-to-day planning at local, national, and cross-border levels. In practice, this means using familiar file formats and simple connections to other systems. Tool should clearly indicate where each dataset comes from and when it was produced, so that users can judge its relevance, and should also allow practitioners to swap datasets and adjust key assumptions without specialist coding. Rather than relying on complex modelling, tools should favour transparent, simple methods that are able to orient choices, reveal trade-offs and distributional effects, and run under real-world constraints. Uncertainty should be embraced through ranges and scenarios that allow users to explore options rather than rely on single "best" numbers. Crucially, tools should also be designed to remain useful with imperfect data and to improve as better evidence becomes available, so that utility does not depend on constant, labour-intensive updating. In this regard, the capacity to scale across governance levels and to

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evolve as data, methods, and user needs change should be treated as core design requirements rather than afterthoughts.

Rather than promising precision, future tools should be designed to work with complexity, including the socio-political processes that shape the contexts they are meant to inform. Risk and adaptation are driven as much by climatic and environmental processes as by inequality, political-economic regimes, and other societal forces. Overlooking these dimensions is amongst the key reasons why adaptation efforts fail or lead to maladaptation. To meaningfully inform adaptation, tools therefore need to recognise and account for these socio-environmental dynamics, including the power relations that govern access to resources, redistribute impacts, and decide whose vulnerabilities are addressed. In practice, tools should incorporate socio-economic datasets and institutional and governance analyses alongside qualitative inputs that reveal how power operates. Doing so helps trace the root causes of vulnerability, adaptation, and maladaptation.

At the same time, tools must reflect the interdependence of hazards and of adaptation measures. Planning remains partial when droughts, floods, heatwaves, wildfires, and coastal hazards are treated in isolation. Effective decision support should illustrate the interactions between hazards and demonstrate how their effects cascade across different sectors and scales. Many decisions cut across water, energy, food, ecosystems, tourism, and urban development, and tools need to make these interdependencies legible by integrating cross-sector data, surfacing synergies and conflicts, and allowing users from different agencies to explore shared scenarios from their own perspectives. The aim is not a single tool for every problem, but interoperable approaches that make coordination feasible. This requires shared data standards, open APIs, and common vocabularies that allow tools to exchange inputs and outputs across sectors. Funding agencies can shift the ecosystem towards integration by requiring interoperability standards, modular architectures, and cross-tool compatibility as conditions of funding, rather than incentivising standalone, project-specific deliverables. In practice, this points towards a modular ecosystem of interconnected tools, where, for example, a climate projection service feeds into a sectoral risk assessment, which in turn informs an adaptation planning framework.

Embracing complexity also means treating adaptation as a long-term socio-environmental transformation rather than a short-term technical fix to an isolated climate hazard. Robust adaptation requires a long-term thinking and iterative decision-making that can respond to uncertainty and the changing dynamics of coupled social and environmental systems. The ecosystem of tools should therefore support the full adaptation cycle, from priority setting and implementation, to monitoring, review, and adjustment while making explicit the long-term implications of alternative choices. Beyond extending the time horizon, integrating citizen science and locally generated data can strengthen feedback loops, broaden the evidence base, and enhance legitimacy. This is especially important given that few tools are currently designed for community organisations or operate at the scale needed for local diagnosis and action. Future developments should enable communities to identify risks, test options, and track progress themselves, supported by multilingual interfaces, offline-options, and modular configurations tailored to sub-regional contexts.

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Delivering this reorientation demands coordinated across developers, public institutions, researchers, and funders. Developers should commit to genuine co-production with local, national, and regional actors, and publish clear roadmaps, documentation, and maintenance plans so that tools remain usable and accountable over time. Policymakers and public institutions should embed tools in routine planning and budgeting, invest in capacity for non-expert users, and align incentives to reward co-production, equity, and impact. Researchers and funders, in turn, should shift their attention from building yet another tool to providing guidance on which tools to use, when, and how. What users need most are syntheses that map the strengths and limits of existing instruments across sectors and scales, typologies that make those differences legible, and decision frameworks that match specific problems to suitable tools. This shift also calls for independent, longitudinal evaluations that follow tool use through real planning cycles, documenting not only technical performance but also the decisions influenced, costs incurred, distributional effects, and unintended consequences. Methodologically, research should continue to advance compound-risk and nexus analytics, as well as transparent ways of combining climate, ecological, and socio-economic evidence so interdependencies and trade-offs are visible rather than hidden in black boxes. Funders should allocate resources not just to innovation but to maintaining and curating existing tools and building pathways for sustainable implementation. Here, maintaining refers not merely to keeping tools operational, but to sustaining and, where necessary, updating their utility and effectiveness as climate risks, data, and understanding of adaptation evolve.

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Methods

Our study systematically evaluates the current landscape of adaptation tools by mapping their key attributes, such as sectoral coverage, geographic and temporal scales, methodological approaches, usability, and accessibility, while assessing the extent to which these tools address the region's distinct vulnerabilities, needs, and priorities. The analysis provides a structured overview of 122 tools and examines critical gaps and opportunities for improving their usability and applicability in practice.

We followed a structured six-phase workflow (Fig. S1) designed to ensure consistency, comparability, and transparency in the evaluation of CCA tools. This workflow guided the identification, classification, and analysis of 122 tools from diverse global contexts, with an emphasis on their relevance to adaptation planning in the Mediterranean region.

Study Design and Systematization Framework

To enable a structured and comparative assessment of the tools, we developed a multi-dimensional systematization framework (Fig. S1, phase 1). The development of the framework and methodological design was informed by a selection of foundational studies that examine the diversity, usability, and sectoral focus of adaptation tools. The references to these studies are summarized in Supplementary (Table S1), which outlines key literature sources and their contributions to the review structure. The framework was designed to capture the diversity of CCA tools in terms of their technical, functional, and operational characteristics, while also reflecting the complexity of adaptation needs in practice, and the classification dimensions listed in Table

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S2 (in Supplementary). This systematization framework served as the foundation for designing the evaluation survey and informed all subsequent stages of the assessment, ensuring systematic data collection across the identified dimensions. A full list of definitions and classification criteria is provided in Supplementary information (Criteria for Tool Systematization (Criteria for Tool Systematization). The methodology adheres to the principles of systematic evaluation and builds on the PRISMA 2020 guidelines[112], which were adapted specifically for the systematic assessment of CCA tools. A customized version of the PRISMA checklist is provided in Supplementary (Table S3).

Eligibility criteria

We defined a tool as an operational, digitally accessible resource that combines information and methods to support adaptation (planning, implementation, monitoring, assessment/decision support, early warning, or education/engagement). A record was included if it (i) explicitly addressed adaptation (not mitigation-only); (ii) was publicly accessible at the time of assessment (URL available); (iii) provided sufficient documentation to populate the classification fields included in Table S2. Static documents without an interactive component, proprietary/internal resources without public documentation, duplicates/superseded versions, and mitigation-only calculators were excluded.

Tool identification and screening

The tools identification (phase 2) began with expert contributions from researchers affiliated with the FutureMed network, complemented by targeted desk research using online databases, adaptation platforms, and project repositories. Searches were guided by the classification dimensions used in this study (Supplementary Table S2). The resulting longlist was then de-duplicated and screened (phase 3) to confirm relevance to climate adaptation and decision-support functions. No tools were excluded at this stage, preserving inclusivity for subsequent resolution during validation. The inventory is representative rather than exhaustive because discovery relied on expert knowledge and publicly available web sources and coverage is likely biased toward English-language and European portals. However, this approach ensured the inclusion of both widely adopted international tools and lesser-known instruments with specific regional applications. Geographic coverage including Mediterranean relevance was recorded as a variable and analysed.

Contributor review

In the contributor survey review (phase 4), each tool was assessed independently by two to three reviewers randomly assigned from the FutureMed network, using a standardized survey designed in line with the systematization framework. The survey captured a range of qualitative and quantitative aspects (see detailed Criteria for Tool Systematization in Supplementary) including tool type, sector focus, spatial and temporal scale, methodological approach, data requirements, usability, and cost model. Both closed-ended and open-ended questions were used to gather structured responses, while also allowing for contextual observations. Any inconsistencies or gaps in responses were flagged for follow-up during the validation process.

Expert validation and harmonisation/classification

A subsequent expert validation (phase 5) was conducted by two senior reviewers who performed a secondary review of all tool entries. This phase served to harmonize data entries, resolve discrepancies, and supplement missing information where needed. Additionally, they identified and added 18 additional tools that met the eligibility criteria, bringing the final inventory to 122

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tools. Final classifications were assigned for each tool following the predefined systematization framework, enabling standardized comparison across the dataset.

Analysis and visualisation

The resulting dataset was analysed (phase 6) to explore key attributes and relationships among the evaluated tools. Key patterns were explored across tool attributes, i.e., the proportion of tools targeting specific sectors or user groups, or the frequency of specific tool types. In addition, cross-tabulation analysis was applied to explore the relationships between dimensions, e.g., between usability and customization, or between spatial scale and data granularity. The results of this analysis were visualized through charts and figures to support interpretation and synthesis. Importantly, this methodological workflow ensured that no tools were excluded during the process; instead, missing information and classification uncertainties were addressed systematically during the validation phase. The final output of this analytical approach is a comprehensive, harmonized review of 122 tools, reflecting both technical capabilities and contextual relevance for Mediterranean climate adaptation.

Data availability

The CCA Toolscape Inventory dataset is available on Zenodo [10.5281/zenodo.17189712 under CC BY-NC 4.0 licence. Furthermore, an openly accessible live inventory has been developed (https://adapt-tools.org/) to enable continuous community engagement with the tool landscape.

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Author contributions

A.K. and E.S. conceived and designed the study. A.K. developed the systematization framework with support from E.S. C.C., I.P., A.P.G., L.V., R.S., S.Z., P.V., I.L., M.T., Z.E., C.P., M.S., F.P., M.T. and N.P.G. contributed to tools identification. A.K. performed initial screening. A.K., E.A.Y., S.A., J.B., M.B., J.B., A.B., R.B., C.C., S.Z., P.C., K.D., Z.E., M.H.E., M.F., N.P.G., E.G., F.H.G., M.G., A.P.G., A.H., Z.İ., K.J., J.K., Z.K., R.K., G.K., E.K.O., B.K., S.K., P.K., S.R., F.O., E.K.O., E.Z.Ö., C.P., N.P., Y.P., K.M.P., N.P.G., I.P., A.P., Z.P., A.R., D.R., C.S.G., M.T., A.T., L.V., P.V., G.Z. contributed to the detailed tool assessment. I.L. and M.T performed expert validation, harmonised classifications across entries, produced figures and visualisations and assisted with result synthesis with the support of S.R and S.Z. Finaly, A.K and E.S wrote the draft, with inputs from A.F., V.H.M, T.T., R.S., M.T., M.S., F.P., S.K., and E.F.

Competing interests

The authors declare no competing interests

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