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Review

REVIEW

Climate change adaptation to extreme heat: a global systematic review of implemented action

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ABSTRACT

Extreme heat events impact people and ecosystems across the globe, and they are becoming more frequent and intense in a warming climate. Responses to heat span sectors and geographic boundaries. Prior research has documented technologies or options that can be deployed to manage extreme heat and examples of how individuals, communities, governments and other stakeholder groups are adapting to heat. However, a comprehensive understanding of the current state of implemented heat adaptations—where, why, how and to what extent they are occurring—has not been established. Here, we combine data from the Global Adaptation Mapping Initiative with a heat-specific systematic review to analyze the global extent and diversity of documented heat adaptation actions ($n = 301$ peer-reviewed articles). Data from 98 countries suggest that documented heat adaptations fundamentally differ by geographic region and national income. In high-income, developed countries, heat is overwhelmingly treated as a health issue, particularly in urban areas. However, in low- and middle-income, developing countries, heat adaptations focus on agricultural and livelihood-based impacts, primarily considering heat as a compound hazard with drought and other hydrological hazards. 63% of the heat-adaptation articles feature individuals or communities autonomously adapting, highlighting how responses to date have largely consisted of coping strategies. The current global status of responses to intensifying extreme heat, largely autonomous and incremental yet widespread, establishes a foundation for informed decision-making as heat impacts around the world continue to increase.

Key words: climate change; extreme heat; adaptation; climate justice.

INTRODUCTION

Extreme heat jeopardizes the well-being of people and ecosystems globally. Individuals, communities, and governments are adapting to extreme heat, but the extent and types of these adaptations vary widely, along with the actors promoting and implementing measures [1, 2]. Additionally, there is limited information about monitoring, evaluation and learning in these adaptation efforts [3, 4]. Whereas climate change impacts are increasingly detected and attributed to human-induced climate change, the global status of climate change adaptation is much less understood [5, 6]. This article provides a systematic review of how heat adaptation responses are unfolding globally as reported in the scientific literature, building from the Global Adaptation Mapping Initiative (GAMI).

Anthropogenic climate change is increasing the frequency and intensity of extreme heat events in many regions [7]. Defining an extreme heat event is highly context dependent and can be a technical and contested exercise, but under any definition, the frequency of these events is growing [8]. Attribution studies have demonstrated significant increases in the likelihood of recent heat waves due to climate change [5], for instance, in Europe [9], Asia [10] and Russia [11]. Under 1.5°C global mean temperature increase above preindustrial levels, around 13.8% of the global population will experience severe heat waves twice a decade (e.g. heat waves similar to the 2007 Balkans or 2015 Central European heat waves) [12, 13]. Considering heat and humidity in a 4°C warming scenario, a heat wave with a magnitude greater than the 2010 Russian heat wave—an event that killed over 50 000 people—would have over a 10% annual chance of occurring in Central Europe, India and many regions in Africa and a greater than 50% annual chance of occurring in the Eastern United States, Northern Latin America and China [14]. Other studies have highlighted the Middle East, North America and South Asia as regions of concern for heat exposure approaching extreme heat survivability and adaptability thresholds under high magnitude climate change [15–17]. In addition to the dangers of chronic extreme heat in the Earth's hottest regions, projected increases in the magnitude and variability of acute heat in cooler places also pose substantial risks [18, 19]. The severity of a heat wave relative to the mean local and seasonal climate is a key driver of impact [18, 20]. The urban heat island effect further exacerbates exposure [21–23]. Hence, under global warming, extreme heat is a major, multifaceted global threat.

The impacts from extreme heat across the world are multifold. Heat threatens physical and mental health [20, 24–27], agricultural yields and land-based livelihoods [28, 29], outdoor workers and their health and productivity [30, 31], transportation infrastructure [32], energy supply [33, 34], biodiversity and ecosystems [35] and human security [36, 37]. These impacts can exacerbate the consequences of other climate-related hazards, such as drought or wildfires, or stressors not related to climate, such as air pollution or civil unrest [38–40]. Extreme heat alone or in combination with other hazards can trigger cascading impacts affecting multiple systems, sectors or regions and challenge effective management of the risks. For example, in India, concurrent heat waves and droughts in 2002 and 2009 negatively impacted agriculture, health and economic sectors and caused terrestrial water storage losses and electricity shortages [41, 42]. Similarly, in 2013, a heat wave in Buenos Aires overwhelmed the electrical grid, leaving 800 000 people without power, which triggered protests around the city [43]. More recently, the 2020 heat wave in Siberia thawed the tundra, causing an unprecedented summer fire in the Russian Arctic [44].

Differences in exposure and vulnerability cause some communities to be more affected by extreme heat than others. Heat-relevant trends that increase exposure or exacerbate sensitivity include urbanization, aging populations and population

growth [45–47]. Exposure and vulnerability [4] to extreme heat are temporally and spatially variable, and the two often influence each other. For example, redlining—a historic practice of disinvestment in Black and brown communities in the USA—is associated with greater heat exposure [48]. Measuring vulnerability to heat is convoluted as aspects that may make some communities more vulnerable to extreme heat impacts may be irrelevant to others. For example, the drivers of vulnerability in urban communities, such as lack of tree canopy coverage or simultaneous air pollution, are not necessarily the same in rural communities [49]. Critically, those with less capacity to adapt to extreme temperatures, such as people living in informal settlements, daily wage earners, the elderly, people who are socially isolated, and people living with mental health issues or chronic disease, are also often most at risk due to nonclimatic drivers [50–56]. Active promotion and focus on equity and justice in climate adaptation have emerged in the literature as a response to these disparities. Adaptations that incorporate distributive, procedural and recognition justice can address the root causes of inequity [57, 58]. Likewise, the extent to which local knowledge and/or Indigenous knowledge figure into adaptation is a critical feature of equitable adaptation [59, 60]. Beyond perpetuating past harms, failure to meaningfully include local knowledge or Indigenous knowledge can prevent the adoption and persistence of strategies and overlooks existing on the ground capacity.

There is no single strategy that can be uniformly applied across all communities. A plethora of research exists on various adaptation responses deployed at local scales, but an integrative understanding of what measures have actually been implemented to manage heat extremes is lacking. This study addresses this knowledge gap by systematically assessing global adaptation responses to extreme heat or heat in combination with other hazards across sectors. It complements recent studies that reviewed urban heat modeling [61], planning for heat [21] and the urban heat-health nexus [22]. In addition to considering what measures are being implemented, we explore why and how these adaptive responses are occurring, as documented in the scientific literature. Through a systematic review building from the GAMI dataset, we explore the following questions: (i) What impacts most commonly lead to adaptation to extreme heat? (ii) What are the roles of different actors in adaptation to extreme heat across scales of implementation? (iii) What types of responses are deployed? and (iv) How are equity, local knowledge and Indigenous knowledge incorporated into heat adaptation responses?

METHODS

Developing the implemented heat adaptation dataset

This work combined data collected from the GAMI project with a systematic review of the literature using heat-specific adaptation searches. GAMI screened peer-reviewed literature published from 2013–19 to identify studies that documented human responses to climate change. After 48 316 articles were screened, 1682 articles were coded based on 65 questions related to response type, depth, scope and speed; actors; hazards and vulnerability; evidence of risk reduction; limits to adaptation; and equity. The methods used to create this database are detailed in the protocols for each stage [62–64]. GAMI follows the 'RepOrting standards for Systematic Evidence Syntheses' guidelines [65].

Here, we first filtered the original GAMI dataset to identify articles describing implemented responses to extreme heat under climate change. We included only articles with 'increased frequency and intensity of extreme heat' coded in the hazards category, which returned 475 articles (Fig. 1). Because some of these articles described responses to mean temperature increases, rather than extreme heat, we filtered for the extreme heat relevant articles by searching for the phrases 'heat', 'hot day', 'hot night', 'extreme temperature', 'temperature extreme', 'extreme minimum', 'extreme maximum' and 'high temperature' in the hazards, responses, implementation, reduced risk, exposure and risk quotes sections of the GAMI database and then manually confirming the relevance of each article to extreme heat adaptation. A total of 202 articles on implemented adaptation to extreme heat or to heat as a compound hazard were thereby extracted from the GAMI database.

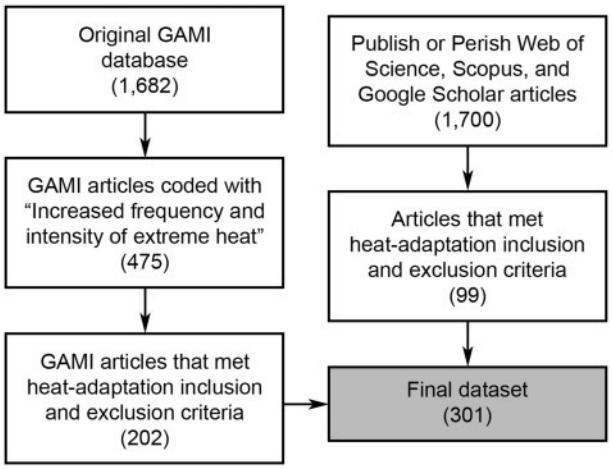

Figure 1: Systematically reviewed articles on implemented extreme-heat adaptation. In total, 301 articles from the GAMI database and additional literature searches met our inclusion criteria for implemented climate change adaptation specific to extreme heat. Numbers in the parentheses represent the articles at each stage in the process.

We then systematically searched for heat-specific adaptations in the literature to identify articles that may have been overlooked in the machine-learning algorithms applied to screen the literature by GAMI. Following the GAMI screening protocol, we included studies that documented or analyzed implemented climate change adaptation in our analysis. We excluded articles that did not include human-assisted responses, that focused on greenhouse gas emissions mitigation, that did not focus on climate change responses, or that were purely conceptual, theoretical, or simulated and model-based. Unlike GAMI, we considered activities such as implemented coordination between government agencies or the creation and administration of adaptation policies or plans as implemented adaptations. Further, we included papers that featured adaptations to extreme heat occurring either in isolation or simultaneously with other hazards such as drought.

Our search, therefore, used additional heat and adaptation-relevant key phrases. Using Harzing's Publish or Perish software [66], which prioritizes most relevant articles, we screened 1000 articles from Web of Science, 500 articles from Google Scholar and 200 articles from Scopus (the allowed software maximum) using the search string ('extreme heat' OR 'heat extreme' OR 'urban heat' OR 'heat wave' OR 'heatwave' OR 'heat health' OR 'heat-health' OR 'hot day' OR 'hot night' OR 'heat day') AND (adaptation OR preparedness OR 'action plan' OR management OR 'hazard mitigation' OR resilience). The term 'heat' by itself was

not included because it returned many articles irrelevant to climate change. All articles published after 2013 were included. Of the 1700 articles screened, 99 met the inclusion criteria and were not already in the GAMI dataset. Hence, our final sample size rose to $n = 301$ articles.

Analyzing heat adaptations

The primary goal of this work was to investigate where, why and how adaptation to extreme heat is unfolding globally. All articles were coded accordingly. The included GAMI data and the additional articles were analyzed to answer questions about impacts addressed, types of responses, actors and inclusion of Indigenous knowledge and local knowledge across geographic regions, as defined by the United Nations [67]. We also considered country groupings by World Bank national income level [68]. A map of country income levels applied is available in Supplementary Fig. S1.

We employed five analyses to address this study's main aim. First, the number of articles for each region was mapped. Second, we sought to understand the specific heat impacts addressed by the adaptations documented in the articles. We grouped these impacts into five overarching categories: health and well-being, economic and human security, agriculture and subsistence livelihoods, infrastructure and the built environment, and socio-cultural impacts. For each of these categories, we also documented all the specific heat impacts addressed through observed adaptations (Supplementary Figs S2 and S3). Both primary and secondary impacts were relevant to documented adaptations. Primary impacts occur in direct response to heat exposure, such as crop failure or decreased productivity. Secondary impacts occur in response to the primary impact, such as loss of income. Third, the hundreds of adaptations to extreme heat were summarized and grouped as infrastructural or technological, institutional, behavioral or cultural, or ecosystem-based adaptations [69]. These categories were chosen over alternatives, such as response vs. preparation and design vs. risk management solutions [21], to match common practices in the climate adaptation literature. Complete detail on the categorization of adaptation strategies is available in our dataset in Supplementary Table S1. Fourth, we analyzed how different actors are involved in extreme heat adaptation. Four actor groups were included: individuals or communities; government; academics, nonprofits and civil society; and private sector, technical professionals and industry. We reviewed each GAMI code and newly identified article to document how and where adaptations were being implemented and by whom. We include analysis of the actors and response types by country in Supplementary Fig. S4. Finally, given that equity and justice concerns are central to adaptation, we examined how equity considerations are incorporated into adaptation responses. Specifically, we considered how local knowledge and/or Indigenous knowledge was incorporated; the integration of equity; timing of stakeholder interactions in and throughout adaptation; agency of local and Indigenous people; recognition and role of local and Indigenous people; and how information was gathered from or with these groups across the articles. Selection of these categories was informed by recent work on co-produced research and Indigenous knowledge in adaptation [59, 78–80]. All observations for this part of the analysis were purely descriptive and do not represent any normative claims from the authors about how participation and knowledge from local or Indigenous groups should be included. Here, the term local communities refers to non-Indigenous Peoples.

RESULTS

By analyzing 301 peer-reviewed articles, this study documents where, why and how people are adapting to the impacts of extreme heat or heat in combination with other hazards across the globe. First, we determine countries and regions in which implemented extreme heat adaptation has been documented. Next, we analyze the diverse heat impacts to which people are responding, the types of adaptations implemented and the actors involved. Finally, we document how local or Indigenous knowledge and/or involvement are incorporated into the heat adaptations. Through this analysis, we assess the global status of implemented extreme heat adaptations.

Extreme heat adaptation by region

Global regions are unequally represented in the heat adaptation literature. Some countries are disproportionately represented in existing literature while others are not documented at all (Fig. 2a). Ninety-eight countries are included in at least one article in our dataset. Australia and the USA are the most studied countries; they are discussed in 49 (16%) and 48 (16%) articles, respectively. India (8%), the UK (8%), Germany (7%), China (7%), Canada (6%), France (6%), Ghana (5%), Nigeria (4%), Bangladesh (4%) Italy (4%) and Spain (4%) are all included in more than 10 articles. Very few articles involve analysis of extreme heat adaptation in Latin America and the Caribbean. Bolivia is most mentioned for the region; however, it is only included in 4 (1%) articles. Eastern Europe, Central Asia and Western Asia have the fewest articles; countries in these regions are covered in 14 (5%) articles, 10 of which are review studies that cover multiple countries across the globe. The exclusion of articles in languages other than English may explain the lack of articles about implemented heat adaptations in Russia, despite its severe 2010 heat wave.

Heat impacts relevant to adaptation

A variety of impacts from extreme heat emerge as relevant to implemented adaptation responses. Impacts are grouped into five categories: health and well-being, economic and human security, agriculture and subsistence livelihoods, infrastructure and the built environment, and sociocultural impacts (Fig. 2b and c). The articles discuss both primary and secondary impacts of extreme heat. Some impacts appear frequently in relationship to implemented responses, whereas others come up in a few articles (Supplementary Figs S2 and S3). The agriculture and subsistence livelihood category substantially overlaps the economic and human security category. These heat impacts are commonly discussed together: 88% of articles that include agricultural and subsistence livelihood impacts also discuss economic and security impacts, and 77% of articles that include economic and security impacts also discuss agricultural and subsistence livelihood impacts. Health and well-being heat impacts are most common in the adaptation-response literature (59% of articles). Health and well-being heat impacts commonly co-occur with socio-cultural impacts and impacts to infrastructure and the built environment. In total, 79% of articles that discuss socio-cultural impacts also include health and well-being impacts, and 79% of articles that discuss impacts to infrastructure and the built environmental also include health and well-being impacts.

Heat impacts are prioritized differently across regions and income levels. Heat-adaptation articles about low- and middle-income countries are primarily focused on heat as an

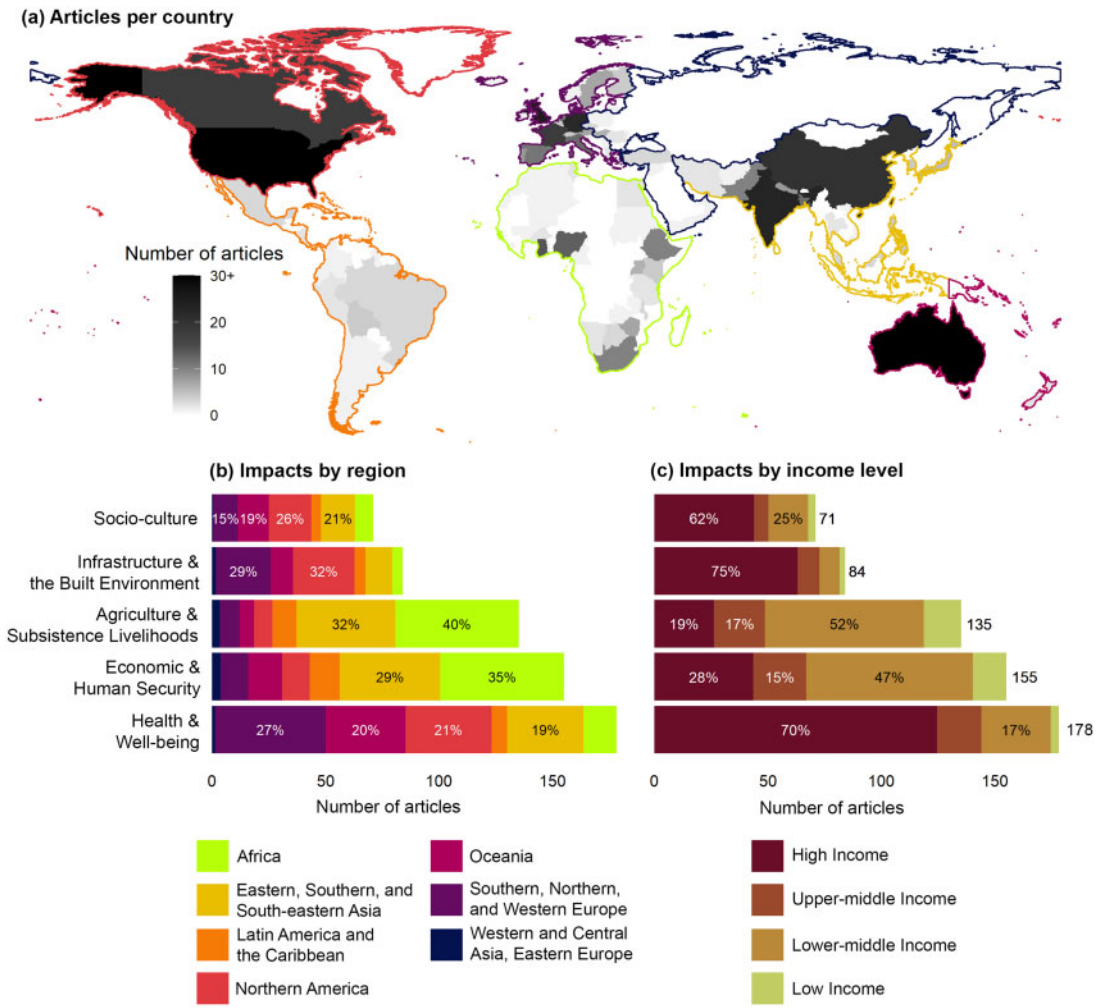

Figure 2: The number of articles about heat adaptations and the impacts they discuss differs by country and region. (**a**) The distribution of implemented heat adaptation articles by country. Fill color represents the number of articles that mention a country, with the darkest shade specifying more than 30 articles. Articles that discuss multiple countries are counted multiple times. Borders correspond to United Nations regions. The numbers of articles that describe the impacts of heat across five categories are shown in panels (**b**) and (**c**). The total number of articles represented by each bar is listed to its right in panel (c)—these values are the same across (b) and (c). Articles that discuss multiple impact categories are counted in each relevant category. Colors from (b) correspond to the regions in (a), and colors in (c) represent country income level; colors are weighted for articles that span multiple regions. Percentages for each region or income level are shown over each color if they are greater than or equal to 15%.

agricultural and economic issue (Fig. 2c). This finding holds for Africa, Eastern Asia, Southern Asia and South-eastern Asia (Fig. 2b). Agriculture-focused articles primarily consider heat in the context of the hydrological system, especially with drought. Consideration of heat as a compound hazard is much less common in the other impact categories. Articles in high-income countries consider the health and well-being; infrastructure and built environment; and socio-cultural impact categories (Fig. 2c).

Types of implemented heat adaptation

A range of adaptation options is observed in response to different heat or compound heat impacts. Outside of Northern America, Europe and Eastern Asia and in low- and middle-income countries, behavioral or cultural responses are the most common (Fig. 3a and b). Infrastructural or technological (28%), behavioral or cultural (26%), and institutional (43%) responses are observed in similar proportions in Southern, Northern and Western Europe. In Northern America, institutional responses are the most common (55%). Across all regions, ecosystem-based responses account for fewer than 15% of adaptations. Each response type is rich with a variety of adaptation options (Table 1) and activities (Supplementary Table S1). For example, 'using weather or climate information' captures the use of scientific forecasts and the use of local skills or Indigenous knowledge to anticipate the weather. Agricultural and subsistence-focused responses are particularly diverse, with many kinds of options discussed across the articles.

Actors involved in heat adaptation

Overall, adaptation to heat, including as a compound hazard, is primarily implemented by individuals and communities. Two hundred and twenty-three (74%) articles discuss communities or individuals involved in adaptation—nearly half (48%) of which do not consider any other actor group (Table 2). Focus on different kinds of actors is most prevalent in Northern America where all groups are above 12% (Fig. 3a). There, adaptation by individuals or communities, with or without other actors, is the

Table 1: Examples of extreme heat responses: behavioral or cultural, institutional, infrastructural or technological, and ecosystem-based adaptations

Type	Examples in the literature
Behavioral or Cultural	'The most common spontaneous adaptation behaviors were "drinking more water", "opening windows", and "resting in the shade". The less commonly reported behaviors were "using a sunshade or sunhat", "bathing frequently" and "going to a public place with air conditioning."' China [70]
	'[A]daptation measures [include] . . . changing from farming to non-farming activities when it is difficult to work on the farm due to intense heat.' Nigeria [71]
Institutional	The Heat Health Prevention Plan 'includes weather forecasts by the State Meteorology Agency, which establishes thresholds to activate different actions of the plan . . . [A]ctions include dissemination of preventive information to the general population and specific high-risk groups and activation of a general hotline and emergency services.' Spain [72]
	Responses from most to least common included 'communication about heat risks and outreach or education to the public[,] . . . collaboration with other organizations, opening cooling centers, or activating existing heat plans[,] . . . assisting with relocation during electrical outages, providing financial assistance, providing transportation, or hiring new staff in response to the heat.' United States [73]
Infrastructural or Technological	Actions included 'installation of air-conditioning, the installation of solar panels to offset electricity costs during periods of high air-conditioning use, insulation, and passive cooling structural design. . .As the increasing frequency and severity of heatwaves was their primary climate change-related concern, the household had built the "cool retreat" which continues to be effective in the event of a blackout.' Australia [74]
	'Respondents dug deep ponds inside the shrimp fields so that shrimps could take refuge from heat stress during summer season.' Bangladesh [75]
Ecosystem-based	'A cocoa agroforestry farmer said that farmers have increasingly planted fruit trees in agricultural plots to create shade to work in.' Bolivia [76]
	'Households either planted or retained trees around their homes and farms to provide shade. This helped to combat intense sunshine and associated extremely high temperatures that were expected to induce heat stress.' South Africa [77]

Illustrative descriptions of types of adaptation to extreme heat or heat as a compound hazard are listed for different countries. As indicated, quotes are edited for readability and brevity. A full summary of all adaptation options is included in Supplementary Table S1.

focus in 30% of the articles. Similarly, actors are most evenly proportioned in high-income countries, where all groups are above 9% (Fig. 3b). In low- and middle-income countries, at least half of the articles discuss communities or individuals adapting. Across contexts, the most common actor/implementation combination is individuals autonomously adapting (63% of articles). Individuals or communities are also involved in adaptation from engagement with the creation of plans, to leading community-level responses, to leveraging social networks for collective and personal good.

Other actors (government; academics, nonprofits and civil society; and the private sector, technical professionals and industry) are involved in adaptation to extreme heat to varying degrees. Overall, government is the second most observed actor group, occurring in 161 articles (53%; Table 2). Government includes local to national-level involvement. Over a third of the articles in the Americas, Europe, Western Asia and Oceania involve government in adaptation (Fig. 3a). Heat adaptations in high-income (40%) countries have similar government involvement as upper-middle- (38%) and low- (36%) income countries. However, despite similar proportions of articles discussing government for each income level, proportions of institutional adaptation differ substantially. High-income countries have a greater proportion (44%) of institutional adaptations than low- (24%), lower-middle- (18%) and upper-middle- (25%) income countries (Fig. 3b). High-income countries are also the only income-level group that includes the private sector, technical professionals and industry greater than 10% of the time. Low-income countries include this actor group in only 2% of articles. Actor/implementation combinations occur at varying frequency (Table 2). Government and the private sector, technical professionals and industry are primarily observed planning, coordinating and educating about risk (Table 2, Row 1). Adaptations for hard infrastructure, such as greening the urban environment, or soft infrastructure, such as developing rosters of at-risk groups for the health sector, are somewhat common.

Indigenous communities and local communities

Indigenous and local communities are reported to be involved in initiatives led by government or other external stakeholders to different degrees. Overwhelmingly the most common way that Indigenous people and knowledge are discussed in the articles is in adapting autonomously using traditional knowledge, animal breeds, crop varieties, practices, rituals, etc. There are a handful of examples of Indigenous or local communities involved in planned adaptation or research on adaptations. We document how these communities are included in knowledge incorporation, integration of equity, the timing of interactions, the agency of local and Indigenous people, and the tools used for gathering information (Table 3). Some forms of engagement such as targeting resources to vulnerable communities or engaging communities in decision-making processes are somewhat common. However, most observations are rare, occurring in only a couple of articles and many only once. Most studies use mixed methods approaches, such as interview or focus group data alongside quantitative data, to assess community or individual perceptions of heat impacts and adaptations. This is primarily the research method used to study autonomous adaptations. Few studies include Indigenous people and local people in research teams from conception of adaptation responses or partner with citizen scientists. We find that Indigenous knowledge and local knowledge are primarily used to fill gaps in

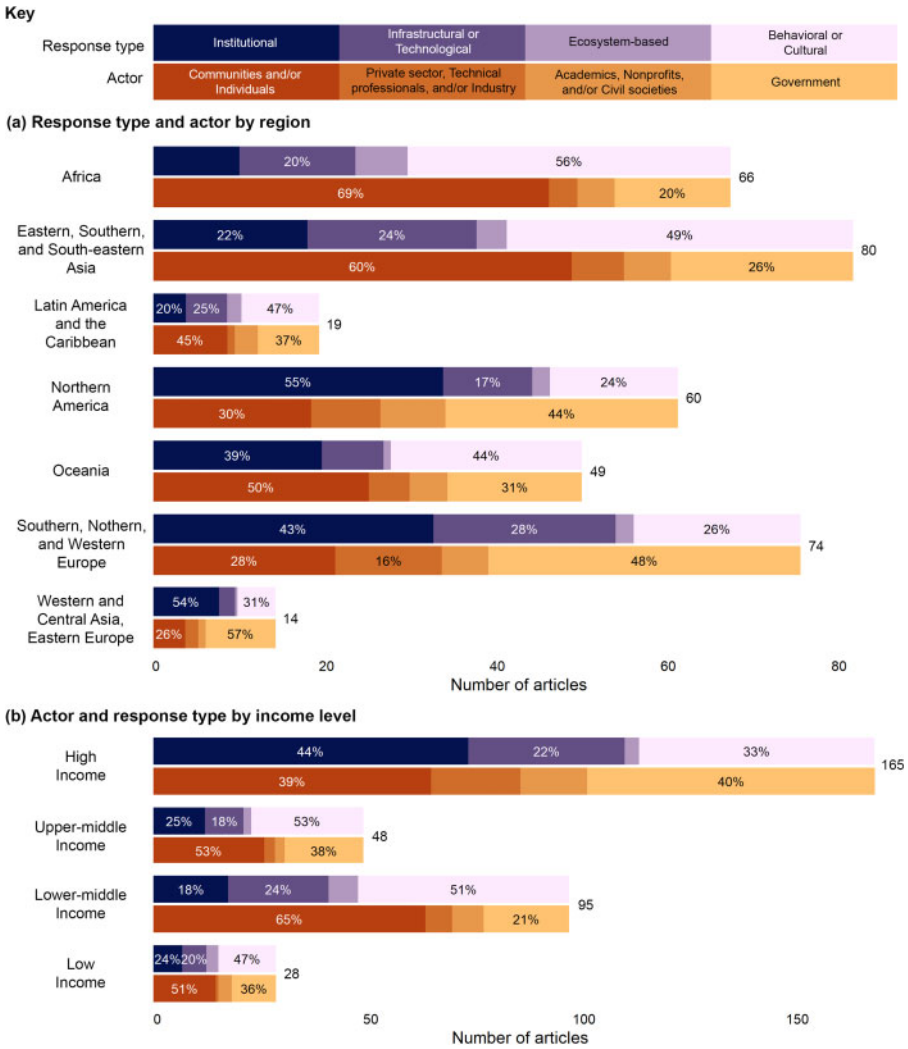

Figure 3: Adaptation response type and implementing actors differ by region and country income level. (**a** and **b**) plot documented heat response types (top bar) and implementing actors (bottom bar). Numbers at the end of each bar signify the total number of articles for that region (a) or country income level (b). Percentages of each adaptation type and actor category are specified within each bar if they are greater than or equal to 15%.

datasets to test existing theories or to assess autonomous adaptation.

DISCUSSION

Across the world individuals, communities, government and nongovernmental actors are adapting to extreme heat. We systematically review 301 peer-reviewed articles about adaptations to heat and heat in combination with other hazards, building foundational understanding of the global status of implemented responses to climate change.

The framing of extreme heat varies substantially by region and national income levels. Health and well-being, infrastructural and built environment, and socio-cultural heat impacts are primarily recognized in high-income, developed countries (Fig. 2b and c). This finding parallels a recent review that found similar geographic biases in the urban heat-health literature [22]. However, in low- and middle-income countries, agricultural and subsistence livelihood, as well as economic and human security, impacts are most common. Focus on these impacts is especially prominent for articles about African countries. These trends are surprising given that much previous work has linked health and well-being as well as agriculture impacts to increased heat exposure across country income levels [81–84]. One study suggests balanced consideration of livestock impacts and adaptation across developing and developed countries, but this review spanned many kinds of hazards, not just heat [85]. Some previous research, however, supports our finding, showing that farmers in high-income countries have low-risk perception of climate change and therefore are likely not actively adapting to it [86]. One alternative explanation could be that in high-income, developed countries articles about agriculture, and particularly crop adaptation, focus on the hydrological impacts without the intersection of heat. There could also be a disconnect between researchers studying impacts of heat and those studying heat adaptation in low- and middle-income, developing countries. Finally, in high-income, developed countries, the urban heat island effect may receive more attention.

Adaptation actors and types of responses also vary across the world. As for heat impact, the types of heat adaptation and actors involved are associated with a country's region and income level. Heat adaptations in high-income countries are evenly spread across different types of responses and actors.

Table 2: Actors planning, implementing and evaluating adaptations in different capacities

Individuals or communities (223)	Government (161)	Academics, nonprofits and civil society (60)	Private sector, technical professionals and industry (68)
	Planning, coordinating, educating and advocating		
• Engaging in adaptation planning with government or nongovernment actors**	• Creating adaptation frameworks, planning documents or indices**	• Assisting in the creation of adaptation plans or strategies	• Technical professionals (engineers, doctors, etc.) providing advice and recommendations**
• Mobilizing or advocating for adaptations or adaptation policies	• Coordinating and collaborating across agencies or sectors or creating task forces**	• Organizing informational workshops and trainings (with industry)	• Industry, professional boards, or NGOs developing or advocating or creating policies for standards or codes*
• Planning their own adaptations*	• Developing policies or issuing directives**	• Promoting or educating people about adaptation activities	• Industry groups researching adaptation options
	• Addressing risk awareness or disseminating information**		
	• Creating, changing or regulating standards or codes		
	• Facilitating, organizing or promoting adaptations		
	Funding, subsidizing and building capacity		
	• Funding adaptation research or seed projects*		• Cooperatives creating incentives and marketplaces or providing economic support
	• Building local or tribal capacity*		• Industry, engineers or architects adopting, influencing, and normalizing adaptation technologies or practices
	• Financing, subsidizing, stimulating or incentivizing adaptation**		• Private actors (citizens, businesses, project developers, associations, etc.) investing in or financing adaptation.
	• Providing loans, insurance or economic assistance programs*		
	Implementing, monitoring and evaluating		
• Using local or traditional knowledge to inform adaptation**	• Tracing illnesses and keeping track of individuals*	• Researchers modeling, simulating or evaluating adaptations that are in place*	• Managers, companies, or unions implementing or leading adaptations*
• **Individuals autonomously adapting*** **	• Distributing supplies, technologies or opening cooling centers	• Checking on or monitoring the well-being of residents	
• Leading, organizing and/or initiating community adaptations*	• Adapting soft or hard infrastructure**	• Implementing, leading, funding or facilitating adaptation efforts**	
• Leveraging social networks to ensure well-being of community members*	• Monitoring or evaluating adaptations		
• Monitoring adaptation effectiveness			

Observations of how different actors are involved in heat and compound heat hazard adaptations in the literature are included for each actor column. Numbers in parentheses represent the number of articles that include that actor—many articles feature several actors. The number of asterisks beside an entry represents the frequency of that observation in the literature. Zero, one and two stars correspond to observations being observed in 2–10, 11–30 and greater than 30 articles, respectively. The bolded observation with three stars occurred in 178 articles.

Previous work reviewing heat planning supports this result [21]. In low- and middle-income countries, by contrast, adaptations are primarily behavioral or cultural adaptations implemented by communities and/or individuals. Across all 301 articles, individuals autonomously adapting using behavioral or cultural responses are the most common form of extreme heat response (Table 2). This is especially true in low- and middle-income, developing countries (Fig. 3b). People, crops and livestock have an optimum climate niche [47] and upper tolerances to heat and humidity exposure. Many regions could approach the human upper limit for survivability under a changing climate [15–17], raising questions about potential limits to autonomous, behavioral adaptations in some locations under increasing climate change. For health impacts, a simple response is greater adoption and use of air conditioning, shown to be extremely effective in reducing detrimental impacts [87]. However, relying on air conditioning also has well-documented barriers and drawbacks such as its cost, reliance on electricity and exacerbation of climate change [88]. The potential for risk reduction from technological, infrastructural, agricultural and subsistence adaptation to heat at survivability thresholds also has uncertainties. Shifting locations of industries, agriculture and human settlements may be other responses increasingly deployed [89–91].

Adaptation to extreme heat presents a significant opportunity to address historic injustices. Inequities in impacts—distributional consequences—are the fourth most common heat impact, reinforcing extreme heat as a hazard with justice implications (Supplementary Figs S2 and S3). We also find that local communities and Indigenous communities are involved to different degrees in planned adaptations (Table 3). Previous work has provided recommendations for or documented examples of co-produced adaptation, which can support procedural justice in the adaption process [92]. However, our results suggest that globally there has been minimal implementation of these techniques to respond to extreme heat. Examples of distributive and recognition justice were more common; many studies discuss

Table 3: Incorporation of knowledge, leadership, participation and agency of local communities or Indigenous people in documented heat adaptations

	Less	Degree of inclusion	*More*
Knowledge incorporation	Local and Indigenous people are consulted with the aim of identifying vulnerable groups or collectives that are or will be highly impacted by heat events.	Local or Indigenous people are consulted to understand their perception of heat wave impacts on resources or sectors and to identify potential adaptation solutions (including autonomous adaptations).*	Engagement of local or Indigenous people into the decision-making process and/or policies. Coproduction of knowledge in heat adaptation activities and/or policies.
Integration of equity	Addressing inequalities or targeting resources to a vulnerable collective.**	Government required to consider equity and vulnerable groups in making decisions.	Heat adaptation responses account for different forms of equity and vulnerable collectives. They have been reached and consulted with prior to and during the research.
Timing of interaction	Contractual or consultative—researchers interact with stakeholders to test or diagnose problems.*		Collaborative action or research. Adaptation or knowledge of the adaptation is cogenerated in partnership, and interactions are continuous and ongoing. Social learning beyond the end of the project is enabled.
Agency of local and Indigenous people	Indigenous people, local people or vulnerable groups are consulted as stakeholders in exploring the problem or designing the heat adaptations.*	Scaling up and supporting existing or new indigenous or local adaptations.	There is a meaningful transfer of power in which Indigenous people, local people, or vulnerable groups own and have agency over the adaptation activity.
Valuing of local and Indigenous people	Indigenous knowledge or local knowledge serves to supplement scientific knowledge.		Indigenous knowledge and/or local knowledge serve to provide governance value.
Tools for gathering information	Use of mixed methods approaches by researchers, combining quantitative survey data with qualitative data from focus group discussions or interviews.***	Community members engaged as citizen scientists, collecting data or information, but not in research design.	Indigenous or local people included in research teams from conception. Engagement with researchers, governments, communities, organizations, and Indigenous knowledge-keepers and leaders.

The first column (bold) lists the categories of local or Indigenous peoples' involvement. The other three columns describe the degree of inclusion of local knowledge and Indigenous knowledge into heat adaptation as a spectrum from less (left) to more (right). Entries originate from the dataset and reflect the language used in the individual studies for strategies found in the systematically reviewed articles. Zero, one and two stars correspond to observations being observed in 1–10, 11–30, and greater than 30 articles, respectively. The observation with three stars occurred in 136 articles.

targeting resources to or identifying vulnerable collectives. Although our results highlight examples of substantial involvement of local communities and Indigenous communities in planned heat adaptations, these were not the norm. We expected more incorporation of equity given its prevalence in climate adaptation literature, particularly for urban areas [5, 57, 93]. This suggests a need to prioritize equity and justice in heat adaptation.

Although we strived to be as consistent and comprehensive as possible in systematically reviewing the global status of heat adaptation, there are several limitations to this study. First, this work is a product of GAMI and therefore subject to its screening and coding [62–64]. Second, as emphasized, there are many ways to define extreme heat, and the delineation between heat and mean temperature increases is not always consistent across articles. A GAMI article is included in our dataset if it was coded for extreme heat in the designated hazard question, included one of the heat-related keywords and was not obviously about general temperature increases. Third, following GAMI's inclusion and exclusion criteria, we have studied peer-reviewed literature. GAMI included articles in all languages, but our supplemental systematic review only considered documents written in English. This may have led us to overlook articles in certain regions or about Indigenous groups. Information about Indigenous groups and their actions may further be limited in our dataset due to data sovereignty and protection of traditional knowledge. Grey literature may also capture how some actors are adapting to heat better than peer-reviewed literature. Finally, an analysis of the efficacy or adequacy of adaptation was not included in this study. An effective strategy is multifaceted, including the ease of implementation, timing and duration of benefits, and reduction of harm or impact [6, 94]. Properly assessing these factors for individual adaptation options was outside of the capacity of our dataset.

Adaptation to extreme heat is happening globally in response to different impacts and at different scales of implementation. We document the status of heat adaptation in 301 articles and across 98 countries. Overall, treatment of extreme heat is fundamentally different across regions and country income levels. This result raises additional questions about future approaches to heat mitigation measures given the changing nature of extreme heat across low and high latitude countries in a warming world. Strategies applied in already heat burdened regions can inform and inspire future adaptation options in other parts of the world. Adaptation is primarily occurring through individuals or communities autonomously responding and coping. Climate change and urbanization will continue to increase the likelihood and severity of extreme heat events, magnifying the need for planned adaptation. Beyond implemented adaptations, there is abundant analysis of adaptation technologies or strategies that could potentially reduce heat exposure, but these responses only matter if they are used. Although there is a lot of work ahead, the diversity and scope of adaptation to heat across the world are an encouraging sign.

SUPPLEMENTARY DATA

Supplementary data is available at *OXFCLM* Journal online.

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AUTHORS' CONTRIBUTIONS

L.L.T.-H., E.C.d.P. and K.J.M. conceptualized and designed research. L.L.T.-H., G.S., E.T.J., E.K.G., E.M.F. and S.E.A. assisted with data collection. L.L.T.-H., R.R.-D., P.N.S. and E.M.F. assisted with data analysis. L.L.T.-H. drafted the manuscript and visualized data. All authors provided input to drafts.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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