Climate change, environmental extremes, and human health in Australia: challenges, adaptation strategies, and policy gaps

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Summary

Climate change presents a major public health concern in Australia, marked by unprecedented wildfires, heatwaves, floods, droughts, and the spread of climate-sensitive infectious diseases. Despite these challenges, Australia's response to the climate crisis has been inadequate and subject to change by politics, public sentiment, and global developments. This study illustrates the spatiotemporal patterns of selected climate-related environmental extremes (heatwaves, wildfires, floods, and droughts) across Australia during the past two decades, and summarizes climate adaptation measures and actions that have been taken by the national, state/territory, and local governments. Our findings reveal significant impacts of climate-related environmental extremes on the health and well-being of Australians. While governments have implemented various adaptation strategies, these plans must be further developed to yield concrete actions. Moreover, Indigenous Australians should not be left out in these adaptation efforts. A collaborative, comprehensive approach involving all levels of government is urgently needed to prevent, mitigate, and adapt to the health impacts of climate change.

Keywords: Climate change; Health impacts; Risk assessment; Climate adaptation; Policy gaps

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Background information about climate change and human health in Australia

Australia is a large island continent in the Western Pacific, extending from the tropics to the temperate region. Despite being a high-income country with advanced health and emergency management systems, it is highly vulnerable to climate extremes and has been caught off-

guard by a series of unprecedented events in recent years. These include the world's largest, most catastrophic epidemic thunderstorm asthma event in 2016,[1] the extensive and devastating wildfires and extreme heat in the summer of 2019/2020–the "Black Summer",[2,3] and the record rainfalls and widespread and repeated flooding in 2021/2022.[4,5] These events overwhelmed emergency management and health systems, and led to considerable acute and chronic health impacts and deaths.[2,4,6]

The cascading and compounding risks of climate change in Australia have been depicted in national and global reports.[7,8] Australia has already warmed by 1.47 °C (±0.24 °C) on average since 1910,[7] accompanied by more frequent and intense extreme heat events.[9] The country has also experienced one of the greatest increases in bushfire risk globally, prolonged droughts in the southern parts of the country, and anticipated more extreme floods in the wetter northern parts.[2,7] These risks are likely to escalate with devastating consequences for Australia's population, economy and environment.[10]

The health and well-being of Australians have been significantly affected by climate change and extreme weather events, resulting in increased incidences of infectious diseases, non-communicable diseases, injuries, malnutrition, forced displacement and mental health problems.[2,4,6] Climate change may also worsen the health inequity that already exists between Indigenous and non-Indigenous populations, low and high socio-economic groups, and rural versus urban populations.[2,4,6] Australian agriculture and food security have been impacted by increased frequency of climate-related disasters. Despite Australia's wealth, recent research has shown that over 2 million Australian households (21%) had experienced severe food insecurity in the previous 12 months, and disasters (e.g., floods, bushfires and droughts) contributed to 19% of the severe food insecurity.[11] Meanwhile, achieving sustainable food and a healthier diet could bring environmental, economic and health co-benefits that outweigh the costs of climate mitigation measures.[12]

Australia has three levels of government (national, state/territory, and local), each with differing responsibilities in relation to health and climate. Regardless of increasing exposure and vulnerability to climate change, Australia's national responses to the climate crisis have been inadequate. Policy engagement by the former Federal Government was inadequate and limited, and climate change and health issues have been addressed in a siloed and disconnected way at the national level.[13] The Australian National Climate Resilience and Adaptation Strategy released in October 2021[14] did not put health at the centre of the policies, which may contribute to the low or decreasing levels of climate concern and impede the recognition and response to climate-related health threats. In addition, there has been little progress in national policy to address the societal-level drivers of health inequity, with culture not recognized as vital to the health and well-being of First Nation's peoples.[15] Moreover, despite a highly urbanised population in Australia, integration of urban planning and public health in climate change policy is rare. For example, Heat Health Action Plans (HHAP), which integrate urban planning and public health actions, can effectively reduce heat-related adverse health outcomes.[16] Although every state has established its own HHAP, there is still a lack of nationally coordinated HHAP. The transition to renewables at a national level is also slow with 32% renewable electricity generation, which is much lower than comparable countries.[4]

The failures of governments to make adequate and urgent climate change policy responses has multiple social and psychological effects. Many people in Australian, particularly young people, feel worry, eco-anxiety, stress, hopelessness/powerlessness and feelings of not having a voice about the lack of adequate and urgent climate change policy responses.[17,18] Climate actions has important roles in mobilising change and enabling social cohesion,[18] but climate policy in Australia has been polarising and depressing.

Australia has made some positive climate relevant policy changes since 2021, such as the AUD 3.2 million to establish the first Australian Centre for Disease Control (CDC) to improve responses to public health emergencies,[19] and AUD 3.4 million to develop Australia's first National Health and Climate Strategy and a National Health Sustainability and Climate Unit by 2023.[20,21] State governments have demonstrated commitments to develop and implement Climate Change and Health Adaptation Plan at a local level, by working with health professionals, academics, non-governmental organisations, industries and communities.[22,23] Another notable state-led development in recent years was the Western Australian Government's Climate Health Inquiry.[24] This was perhaps the first statutory inquiry anywhere in the world focused on the health impacts of climate change.

These changes bring more opportunities to engage policy and decision makers and various stakeholders and agencies for better climate governance and national coordination, collaboration, and solidarity to address the climate-related health crisis. Australian health professionals have increasingly advocated for more ambitious climate policies. The Australian Medical Association (AMA) declared climate change as a health emergency in 2019, followed by other national health and medical associations, e.g., The Royal Australasian College of Physicians (RACP). A 2022 Australian Academy of Health and Medical Sciences (AAHMS) report highlights climate change as an urgent health priority.[25] It reiterates that the health and medical research sector can play an important role by promoting recognition, advancing knowledge, supporting

interdisciplinary research for health co-benefits and amplifying First Nation's voices in decision-making. From the historical National Climate Change Adaptation Research Facility (NCCARF)[26] to the recently established Healthy Environments And Lives (HEAL) Network[27] and the *MJA-Lancet* Countdown Australia,[28] Australian scholars have conducted pioneering, transdisciplinary research to support evidence-informed, integrated, and multidisciplinary climate change adaptation and mitigation policies and practices for a shared vision that enables a climate-resilient, sustainable healthcare system to promote Australia's health under a changing climate.[29,30]

Key climate-sensitive health risk factors

Heatwaves

Heatwaves have been identified as a major threat to human health. From 2000 to 2019, 2296 deaths were associated with heat-related temperatures per year in Australia.[31] The associations of heatwaves with mortality and morbidity may involve most organ systems.[32] For example, the brain's regulation of vasodilation, which physiologically redistributes blood toward the skin to help maintain body temperature during heat exposure, can increase cardiovascular strain. This may result in cardiac ischemia and infarction in individuals with pre-existing cardiovascular conditions.[32] Sweat production, which can reach >1 liter per hour, has the potential to increase the risk of dehydration if lost fluids are not adequately replenished, resulting in kidney injury and failure.[33–35] People with impaired thermoregulation, due to advanced age (e.g., over 65 years of age) and/or medical comorbidities (e.g., chronic cardiorespiratory conditions, diabetes), are particularly vulnerable to the adverse health effects associated with extreme heat especially if they have limited behavioural adaptive capacity (e.g., isolated, low resource living conditions, poor access to healthcare, working in hot environments).[32] Babies and young children are at greater risks because of both high surface area-to-mass ratios and low behavioural adaptive capacities.[36] Several studies in Australia have shown that people who are more socio-economically disadvantaged and remotely located are more vulnerable to the health impacts of heatwaves.[33–35]

Over the period of 2000–2022, most Australian communities experienced at least 10 days of heatwave per year, and the number of heatwave days was often higher than 15 days per year in Queensland and Northern Territory communities (Fig. 1, see definition of heatwave in the footnotes of this figure). The average number of heatwave days per year experienced by Australians showed a clear upward trend from 2000 to 2019, peaked at 25 days in 2019, then decreased to a low level in 2021 and 2022.

In the 2018–2019 summer season, Australia encountered a prolonged and severe heatwave episode that persisted for more than two months, affecting multiple regions across the country and resulting in several unprecedented high-temperature records. In January 2019, the Australian Bureau of Meteorology documented the country's highest-ever recorded average temperature, e.g., the temperature soared to a record-breaking 46.6 °C in Adelaide. Moreover, the heatwave had a compounding effect on the intensity of bushfires that inflicted severe damage to several parts of the country, causing significant loss of life and property.[37]

The pronounced heatwaves have significantly increased the mortality burden in Australia. Between July 2010 and January 2019, heatwaves characterized by an elevated excess heat factor (an intensity measure that categorizes heatwaves by their severity) in Queensland were associated with a 5% increase in all-cause mortality compared to non-heatwave days.[38,39] Individuals aged 80 years and older were particularly vulnerable to these heatwaves.[39] Likewise, another study investigated the heatwave-related impacts on mortality within three Australian cities during the period 1988–2009, and found that heatwaves were associated with an increase of 13%, 10%, and 6% in non-external causes mortality in Brisbane, Melbourne, and Sydney, respectively.[40]

Bushfires

Bushfires, also known as wildfires, are a major climate-related health risk for the Australian population. The health risks associated with bushfires include direct effects from exposure to flames and heat or involvement in bushfire events, such as burns, injuries, mental health, and death, as well as a wide range of health risks from exposure to bushfire smoke,[41] such as eye irritation and corneal abrasions,[42] cardiorespiratory mortality and morbidity, and adverse birth outcomes.[43] Elderly people, children, pregnant women, outdoor workers, and people with pre-existing cardiorespiratory conditions or living in disadvantaged communities are more susceptible to health risks related to bushfire smoke.[41]

Among various air pollutants emitted by bushfires, particulate matter (PM) with a diameter of 2.5 μm or less ($PM_{2.5}$) is the most important because it can travel hundreds of kilometres and affect a vastly larger population than the source fires and has the greatest body of evidence for adverse health impacts. Through entering the lungs, bushfire-sourced $PM_{2.5}$ can translocate through the alveolar epithelium and enter the circulation, subsequently leading to oxidative stress, inflammation, and mitochondrial and nuclear DNA methylation.[44] Compared with urban-sourced $PM_{2.5}$, bushfire-sourced $PM_{2.5}$ tends to have a smaller particle size and contains more oxidative components (e.g., oxygenated polycyclic aromatic hydrocarbons and quinones) and proinflammatory components (e.g., aldehydes and oxides of nitrogen), exhibiting stronger toxicity.[41]

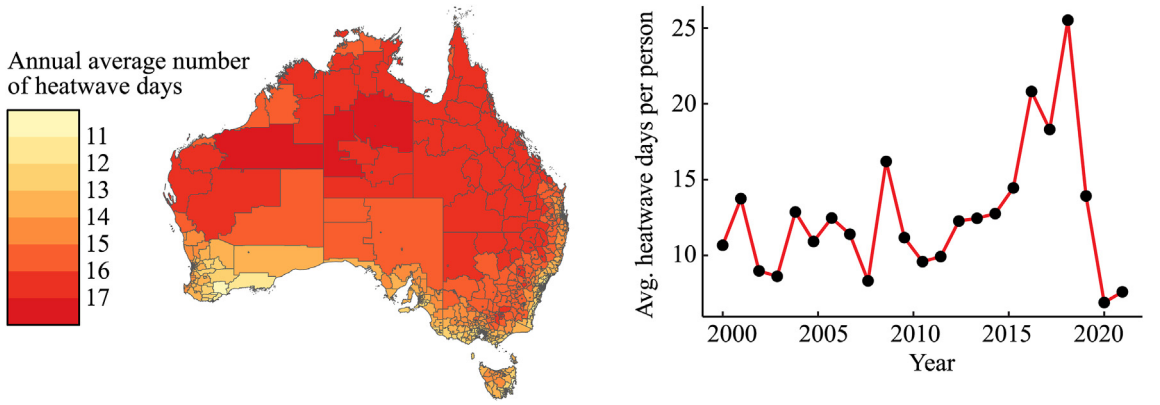

Fig. 1: Spatial (left) and temporal (right) distribution of heatwave days in Australia from 2000 to 2022. Notes: We defined a heatwave in each statistical area level 2 (SA2) area as a period of ≥2 days with daily mean temperature above the 95th percentile of daily mean temperatures in that SA2 area. See Supplementary Materials for detailed methods for this figure.

Bushfire smoke also contains many well-recognised toxic gases including carbon monoxide and oxides of nitrogen and sulphur and is associated with the formation of tropospheric ozone (O_3). These oxidant gases can also amplify the adverse health impacts of bushfire-sourced $PM_{2.5}$. Over 2000–2019, most inhabited areas of Australia experienced at least one day of exposure to substantial fire-related air pollution (SFAP) defined by high levels of fire-sourced $PM_{2.5}$ and O_3 (Fig. 2, see definition of SFAP in its footnotes).[45] Many regions in Northern and Southeast Australia experienced over 20 days of SFAP per year. The average days of exposure to SFAP per person per year have fluctuated substantially in Australia from 1 day to 31 days over the period, peaking at 31 days in 2019, followed by 25 days in 2002.

In Australia, the largest bushfire event in recent decades has been the bushfire in the summer of 2019–2020, commonly referred to as the "Black Summer" bushfires. It caused 34 direct deaths, killed an estimated 3 billion animals, destroyed more than 5900 houses and burned over 24 million hectares of land.[46,47] The smoke from the bushfires affected air quality both at the lower and higher reaches of the atmosphere. For example, compounds transported into the stratosphere by the Black Summer Australian fires in 2019–2020 caused extreme perturbations in stratospheric gas composition that have the potential to destroy ozone.[48] Depletion of the stratospheric ozone layer can lead to increased solar UV-B radiation at the surface of the Earth, which is likely to have had an impact on human

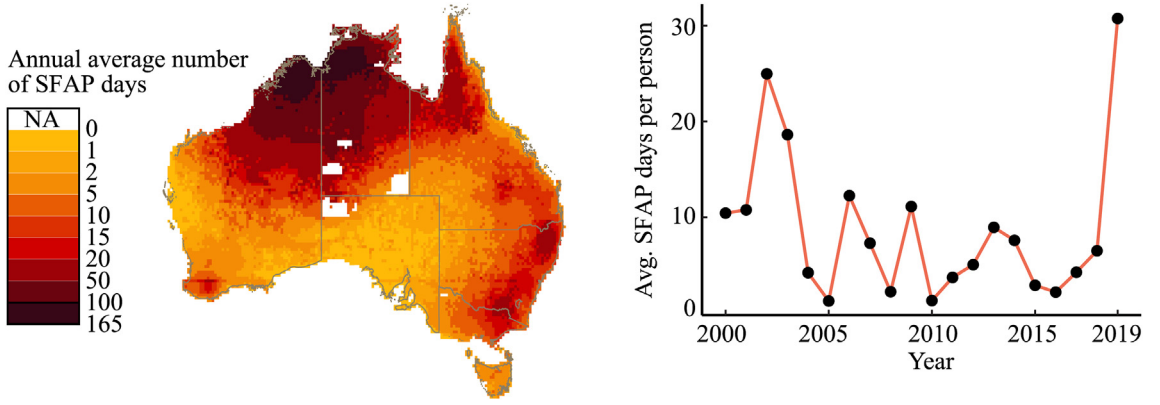

Fig. 2: Spatial (left) and temporal (right) distribution of days exposed to substantial fire-related air pollution (SFAP) in Australia from 2000 to 2019. Notes: NA refers to pixels with no population during the period. A day with SFAP is defined as at least one of the following scenarios: (1) the daily average $PM_{2.5}$ (all-source $PM_{2.5}$) exceeded the WHO's 2021 daily guideline value (15 μg/m^3), and the landscape fire-sourced $PM_{2.5}$ accounted for at least 50% of the daily $PM_{2.5}$; (2) the daily maximum 8-h O_3 (all-source O_3) exceeded the WHO's 2021 daily guideline value (100 μg/m^3), and the landscape fire-sourced O_3 accounted for at least 50% of the daily O_3.[45] See Supplementary Materials for detailed methods for this figure.

exposure to UV-B radiation with consequential detrimental effects on health.[49]

In eastern Australia, population exposure to bushfire $PM_{2.5}$ during the "Black Summer" was estimated to be responsible for 417 excess deaths, 1124 cardiovascular and 2027 respiratory hospital admissions, and 1305 asthma-related emergency department presentations.[50] Another study in Sydney reported a 3.2% increase in all-cause death associated with per 10 $\mu g/m^3$ increase in bushfire-sourced $PM_{2.5}$ over 3 days following exposure, with most of the premature death in those over 65 years of age.[51] Increased use of healthcare services related to bushfires was also observed.[52] As estimated by a study in New South Wales, the bushfire season in 2019–2020 was significantly associated with 6177 excess emergency department visits for respiratory diseases and 3120 excess emergency department visits for cardiovascular diseases, and regions with lower socio-economic status experienced greater bushfire-related excess emergency department visits.[52] A detrimental short- and long-term psychological toll was also observed during bushfires, with numerous Australians suffering from post-traumatic stress disorder (PTSD) and other mental health issues such as major depressive episodes, psychological distress, and alcohol misuse.[53–55]

Moreover, bushfire-related economic costs were substantial. The total smoke-related physical health costs during the 2019–2020 bushfire period have been estimated at AUD 1.95 billion, surpassing the next highest estimate of AUD 0.57 billion in 2002–2003, and exceeding nine times the median annual bushfire-associated costs for the previous 19 years, valued at AUD 0.21 billion.[56] Australia and other regions of the world are likely to see more severe bushfires over the coming decades.[56] Thus, addressing the impacts of bushfires and bushfire smoke is a complex worldwide policy challenge that requires a range of strategies at local, national, and global levels.[41,57] The substantial health impacts of bushfires on large human populations are a compelling reason to fast-track climate change mitigation and adaptation interventions.[58]

Floods

Floods are another climate extreme that poses a significant threat to health in Australia. As the climate warms, heavy rainfall events are expected to continue to become more intense,[59] which will increase flood risks. As shown in Fig. 3, Queensland is the state most impacted by floods, with New South Wales (NSW) being the second most impacted. Capital cities are home to 67% of the country's population[61]; the capital cities of Western Australia, South Australia, Victoria, Tasmania, and Australian Capital Territory (ACT) experienced <1 day of floods per year during 2000–2020. The capital cities of Queensland, NSW, and Northern Territory experienced 3–6 days of floods per year during 2000–2020.

Overall, the flood events caused significant infrastructure and property damage and direct and indirect effects on health in eastern Australia in recent years. Floods in 2022 in southeast Queensland and northern NSW caused AUD 4.8 billion in insured damages, representing the third costliest extreme weather event in Australia's history.[62] This flood event caused the inundation of over 20,000 homes inundated in southeast Queensland alone.[63] Moreover, all public transport services were shut down for several days and southeast Queensland's rail network suffered extensive damage resulting from landslips.[64] Several major highways were also closed due to flooding.[64] The region of northern NSW was also heavily affected by recurrent flood events, which disrupted timely access to health and social services.[65]

Floods can have direct and indirect effects on human health. First, floods can contaminate water and food supply systems.[66] As a result, the risks of gastrointestinal diseases and some infectious diseases can be increased.[67] Second, breeding grounds are often created for fungi, bacteria, viruses, and vectors (e.g., mice, cockroaches, and mosquitoes) post floods, with the potential to trigger outbreaks of infectious diseases.[31] Moreover, flood events can force people to move to temporary accommodations, in which hygiene issues and poor access to medical and health facilities are common.[68] In addition, a range of health impacts can be induced by disaster-related mental disorders.[69,70]

Several studies from Australia showed that flood exposure was associated with poorer respiratory health,[71] increased risks of suicide,[72] PTSD,[73] anxiety, psychological distress, and poor sleep quality,[71] as well as increased use of tobacco, alcohol and medication.[74] However, more study is warranted to better define the longer-term health impacts of floods and to determine the optimal preventive measures, interventions and disaster response strategies that will strengthen resilience to Australian flood disasters.[75]

Drought

Drought can be defined in many ways and means different things in differing sectors of the community.[76] The most salient definitions relate to climatic drought and agricultural impact. Droughts, such as the 'Millennium Drought' in southeast Australia during 2001–2009, can last for a decade, with combined effects from low rainfall, heat, evaporation, and sunshine. Droughts can also be experienced as a short period with extremely dry conditions such as the 2019 "flash drought".[77,78] Due to relatively modest and fluctuating annual precipitation, Australia is widely regarded as a water-scarce country, which renders various regions of the country prone to recurring droughts.[79]

The pathways by which drought can impact health are complex, predominantly involving indirect connections.[80]

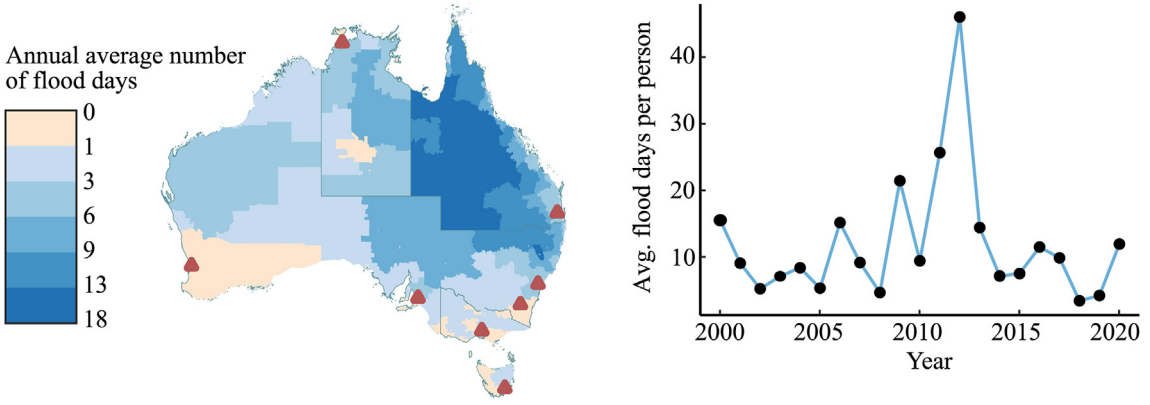

Fig. 3: Annual average number of flood days (left) and annual number of days exposed to floods per person (right) in Australia, 2000–2020. Notes: Triangles represent the capital cities of each state/territory. Some islands are not included (Flood event boundaries, start dates, and end dates were retrieved from the Dartmouth Flood Observatory (DFO)[60]). The map in this figure should not be interpreted as a map of flood occurrence which is spatially discontinuous within each community. It should be interpreted as the average days of each community impacted (i.e., being inundated or being impacted indirectly through various pathways such as water and food supply chain, interrupted transportation and health services) by floods per year. See Supplementary Materials for detailed methods for this figure.

Droughts are associated with increased risks of bushfires, dust storms and heatwaves,[80] which can induce increased mortality and cardiorespiratory problems as mentioned in previous sections of this paper. Drought can cause water scarcity, impairing both water quantity and quality, which is a central pathway of its many far-reaching potential health impacts.[80,81] For example, as water supply is closely associated with environmental sanitation and personal hygiene,[82] drought-induced water scarcity may increase the risks of infectious illnesses due to microbiological and chemical contamination.[83] Furthermore, water scarcity can threaten livelihoods and crop yields, which can cause food insecurity, reducing both the quantity and affordability of healthier food supplies (e.g., fruit and vegetables) and exacerbating nutrition-related health problems.[84,85] Drought may also induce mental health problems, with the potential pathway of socioeconomic losses, displacement, and food insecurity.[85–87] Certain communities are particularly vulnerable to the impacts of drought, including rural communities who depend on agricultural industries, and urban communities who are impacted by the loss of ecosystem services such as air or water quality.

Overall, western and southern Australia experienced more drought than other areas of Australia over 2000–2020, and over 50% of the lands experienced at least 1 month of drought during the two decades (Fig. 4). In recent years there have been alternating drought and flood conditions in many areas of Australia. The eastern states were particularly impacted by an extreme (but short) drought between 2018 and 2019 which followed very wet weather and floods in 2017. Prior to that, there was severe drought from 2006 to 2009 which was broken by a record-breaking rainfall during the 2010–2012 La Niña years.[89]

Climate change adaptation measures and activities in Australia

The Australian Government released the first National Climate Resilience and Adaptation Strategy in 2015,[90] and all levels of governments have been trying to prepare for climate change. The strategy was updated in 2021 to highlight national adaptation priorities that attempt to position Australia to anticipate, manage and adapt to climate change, but health was not placed at the centre of the strategies.[14] The National Strategy for Disaster Resilience was developed to build a more disaster-resilient nation.[91] It outlines a coordinated and integrated approach to managing risks, and focuses on prevention, preparedness, response, and recovery. However, it is necessary to acknowledge that considering the vulnerability of the Australian population, there is still considerable scope for enhancing the existing coping strategies.

Supplementary Table S1 lists adaptation strategies, plans and activities documented by Australia's three government levels. The adaptation measures addressing different aspects of climate change and health in Australia are detailed below.

Adaptation to heatwaves

Heatwave health adaptation in Australia broadly consists of two primary components that focus on immediate heat-health risk reduction. The first is defining the severity and timing of an impending heatwave, which is a service delivered by the national Bureau of Meteorology (BoM). The second is the dissemination of information that identifies who is at the greatest heat-health risk, and the actions that should be taken to reduce this risk, typically via heat-health campaigns delivered by state or territory level health ministries or

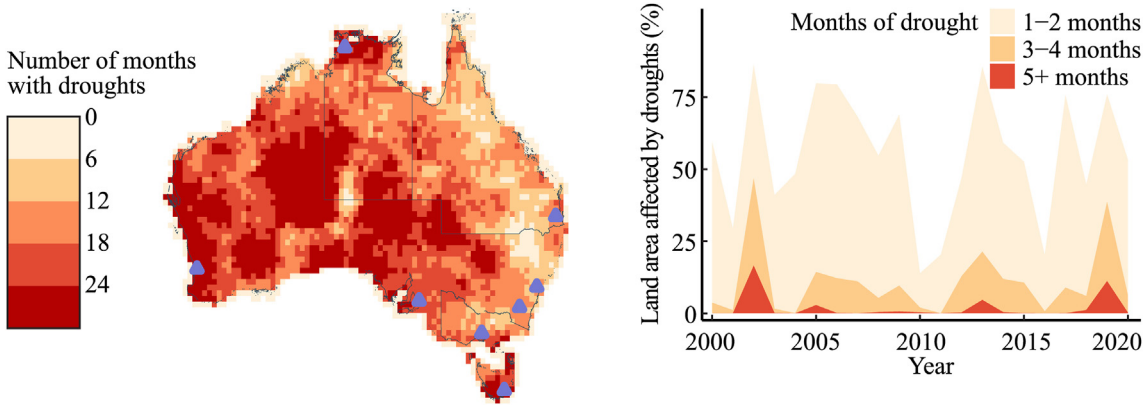

Fig. 4: Number of months with droughts in Australia during 2000–2020 and land area affected by droughts for different numbers of months for each year over 2000–2020. Notes: Standardised precipitation-evaporation index (SPEI) were obtained from the SPEIbase v2.8 (https://spei.csic.es/database.html, accessed on 1st May 2023), with a spatial resolution of 0.5° × 0.5° and a temporal resolution of one-month. Places with drought events are defined as pixels with a monthly SPEI ≤−1.5.[88] The left figure demonstrates the total number of months with drought events for each 0.5° × 0.5° area in Australia over 2000–2020.

departments. Some jurisdictional governments in Australia also have emergency management plans with specific subplans describing control and co-ordination arrangements across multiple agencies for aspects of the preparation for, response to, and immediate recovery from a major heatwave.

In late-2022, the BoM commenced issuing nationally consistent public heatwave warnings for "severe" and "extreme" heatwave conditions within the next 4 days.[38] Each warning includes the level of the heatwave, the timing of when the heatwave will peak, and a map of the warning areas. Warnings are also sent to relevant Health and Emergency agencies and issued across a variety of platforms including the BoM website and Weather App.

All Australian state and territory government health ministries publish public-facing information advising which population groups are most at risk during heatwaves as well as heat protection advice to reduce heat illness risk. This information is often distributed in a variety of formats including posters, fact sheets, checklists, heat alert press releases, and websites. Supplementary Table S2 summarises the most commonly documented advice from publicly available information by each Australian state and territory, which broadly focuses on personal level actions that can be taken to reduce the risk of heat illness during a heatwave. Drinking plenty of water is imperative for replenishing sweat loss and reducing excess cardiovascular and renal strain caused by dehydration.[32] Wearing light-coloured loose-fitting clothing prevents the impedance of sweat evaporation, the principal mechanism of physiological cooling.[92] While potentially expensive and inaccessible to many heat-vulnerable people in remote regions, air conditioning units are owned by 3-in-4 Australians and their use is protective against heat stress.[93] Evidence supporting the efficacy of sun protection (e.g., sunscreen, hats) for directly reducing heat stress is weak, but skin damage from ultraviolet radiation can impair the ability of sweat to reach the outer skin surface and thus potentially blunt evaporation.[94] If air conditioning is not available, electric fans can provide cooling. Biophysical modelling supported by human physiological data indicates that fans can provide cooling in hot conditions, but this effect diminishes with rising temperatures and is dependent on humidity. Fans should not be used above ~40 °C as they can accelerate body heating and worsen physiological heat strain.[95]

In addition to these government initiatives, other activities respective to urban planning are undertaken at the local level. For example, street trees and urban forests yield notable climate amelioration by their cooling impacts such as in Canberra.[96] Installing vegetated or living roofs on suitable buildings, developing more lakes, ponds and wetlands that provide cooling services, and prioritising urban greening to blunt temperature rises associated with the urban heat island effect can have both climate adaptive and health equity benefits.[96,97] Specifically, improving urban amenities and housing design aids low-income residents in reducing energy expenses for climate conditioning and reduces their heat-related health risks. However, the widespread implementation of these and other interventions at the landscape and building levels of the "heat cascade", which determine the level of heat stress to which people are exposed,[93,95] have not yet been broadly mandated by any government.

Adaptation to bushfires

In Australia, health adaptation to bushfires has two components. The first involves responding to bushfires that pose a direct threat to human health and life

through the application of commonwealth, state and territory disaster and emergency management frameworks. The second involves reducing the impact of bushfire smoke on public health.

Bushfire risk management and its gaps

As the risk of bushfires has been increasing over many years, governments at all levels in Australia have responded with comprehensive disaster and emergency management frameworks. In September 2022, the National Emergency Management Agency was formed to provide national strategic oversight and coordination during major bushfire disasters.[98] There is also a nationally agreed three phase approach for implementation of emergency warnings during bushfire (and other emergency) events in Australian states and territories. This Australian Warning System was designed to reduce risk to life through early and consistent warnings.[99] Most local governments have emergency management or specific bushfire plans that outline bushfire risks and steps to minimise risks to human life.[100] Lastly, the Fair Work Ombudsman defines inclement weather provisions for industrial awards to include bushfire, meaning any employees subject to such a provision can be required stop work or redirected to safer duties during a bushfire.[101]

As the risks of bushfires become larger and more frequent, successful adaptation will require the upscaling of existing physical resources and the health workforce to enhance direct responses, for example, increasing the capacity of emergency and burns medicine and hospital and ambulance services. There is a need for increased resourcing for local governments to support community education campaigns and reduce bushfire risk. Resourcing is also needed in the bushfire recovery phase to improve services for displaced people and increase mental health care. In addition, improved urban planning, land use management, and application of building codes and standards (e.g., location, distribution, density, and flammability) can also reduce bushfire risks.[96] For example, due to its diminished flammability compared to pines or eucalyptus, deciduous broadleaf species could be employed in fuel reduction zones to alter fire behavior and impede fire propagation.[102]

Bushfire smoke management and its gaps

Bushfire smoke exposure is an underdeveloped aspect of government adaptation policy. The health impacts from smoke considerably exceed the health impacts from destructive fires.[50,103] While many commonwealth, state, and territory resilience, adaptation, and air quality policies describe bushfire smoke risks, few provide evidence of effective adaptation actions to protect public health. Notable direct adaptation measures are the Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology Air Quality Forecasting framework (AQFx), originally developed to manage prescribed burns in the state of Victoria but now extensively used to forecast bushfire smoke exposure.[104,105] The Commonwealth's Environmental Health Standing Committee provides guidance for public health agencies on managing prolonged smoke events from landscape fires.[106] Safe Work Australia recognises bushfire smoke as a potential workplace hazard that requires risk reduction in line with work health and safety laws.[107] Victoria has established a multi-agency State Smoke policy framework that supports a multi-sector response to the management of significant smoke events.[108,109]

Policy attention is needed to identify groups most vulnerable to bushfire smoke, including understanding regional and local scale human smoke vulnerability to plan targeted warnings and other prevention responses.[110] Local governments should consistently include smoke health risks in municipal bushfire planning.[108] Both state and local governments should work more closely to assess smoke vulnerability at regional and local scales.

In order to successfully adapt to bushfire smoke risks, further research and policy development are required in the following areas[57]: nationally consistent real-time air quality monitoring, public education, vulnerability assessments, warnings targeted at at-risk groups including people with pre-existing illness, mask access and messaging, outdoor worker safety, building ventilation designs, safe air shelters, secure access and supply of medicines, increased access to health services, flexibility in public event timing and venues, and cross-jurisdictional smoke management.

Both bushfire emergency management and bushfire smoke management are not mutually exclusive, but their management often arises from different government agencies. In general, bushfire warnings and smoke hazard alerts are issued by fire and emergency management agencies, while detailed smoke health warnings come from public health or environmental agencies.[111–113] Co-operation and cross-jurisdictional collaboration are critical to promoting consistent responses, increasing community confidence and reducing conflict or duplication in responses across Australia.

Adaptation to floods and drought

Adaptation to floods

The National Flood Risk Information Portal was established to provide up-to-date flood risk information and tools to help individuals, communities, and businesses understand and manage flood risks.[114] The government also developed a National Disaster Risk Reduction Framework to provide a national approach to disaster risk reduction which outlines the roles and responsibilities of different stakeholders in managing flood risks.[115] The Australian Government has also

invested in flood mitigation infrastructure such as levees, dams, and other water management systems to reduce the impact of floods on communities.

These policies and measures are aimed at reducing the impact of flooding on individuals, communities, and businesses in Australia. However, it is important to note that flooding remains a significant challenge in many parts of the country, and ongoing efforts are needed to manage and adapt to its impact.

All states and territories have developed specific guidance documents or plans to address flood management including disaster response (Supplementary Table S1).[116–121] They reflect the state/territory governments' commitment to managing flood risks and building disaster resilience within their jurisdictions. They provide a comprehensive approach to flood risk management, including prevention, mitigation, preparedness, response, and recovery. These documents provide instructions, strategies, and frameworks for dealing with floods and other related emergencies. They recognize shared roles and responsibilities among government agencies, emergency services, the community and many stakeholders. Emphasis is placed on floodplain management and preparedness through planning, training, and education, aiming to enhance community resilience and ensure effective response for the safety and well-being of individuals and communities.

States and territories have unique geographic and climatic conditions that influence floods. Strategies and plans are customized accordingly. Legal and administrative frameworks differ, impacting roles and responsibilities. Specific flood risks, community demographics, and infrastructure vary, leading to diverse focus areas, priorities, and challenges. Resource allocation disparities affect the implementation of flood management strategies.

Many local governments in Australia have developed flood adaptation policies and measures to reduce flood impacts which often complement the national and state-level policies and may be tailored to address the specific risks and challenges faced by the local community. These include:

- Floodplain management plans to guide land-use planning and development in flood-prone areas.[122,123] These plans often include measures such as building codes, zoning regulations, and flood warning systems.
- Stormwater management systems to reduce the impact of flooding caused by heavy rainfall. These systems may include infrastructure investments such as drainage systems, culverts, and retention basins.
- Community engagement and education to raise awareness of flood risks and provide education on flood preparedness and response. This may include community events, workshops, and information campaigns.
- Emergency response and recovery plans to manage the impact of floods when they occur. These plans may include evacuation procedures, emergency shelters, and support services for affected residents.

Overall, local governments play an important role in managing flood risks and protecting their communities from the impact of floods. By working with the national and state governments, as well as local communities, local governments can develop effective flood adaptation policies and measures that address the unique challenges faced by their community.

While flood adaptation strategies in Australia have made significant progress, there are still gaps, including limited integration of climate change projections in relation to rainfall, inadequate long-term urban development planning, communication and community engagement issues, resource constraints, and the underutilization of Indigenous knowledge.[124–126]

Adaptation to droughts

In 2020, a major review of drought policy in Australia investigated initiatives such as the Future Drought Fund, interest free loans, and investments to local economies under the Drought Communities Programme.[127] That review found that most initiatives had positive impacts on farmers and communities, however, it also highlighted several key opportunities for improvement such as weather forecasting for drought indicators, and cooperative research centres to better collate and share information on drought support programs. An important insight from reviewing the history of Australian drought adaptation policies relates to financial welfare support payments. Previous policies were poorly targeted, and risked distorting farm input prices or working as "a disincentive for farmers to prepare for droughts".[76]

Modelling by the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) shows that for cropping farmers, profits of around AUD 230,000 in a typical year may become a loss of AUD 125,000 in a dry year. For beef farmers, profits may fall from AUD 60,000 in a typical year to a loss of AUD 5000 in a dry year.[128] The Australian Government is committed to contributing several billion dollars to support drought-affected communities supporting agricultural and other small businesses, education, health and water infrastructure. To assist rural communities cope with drought, the Australian Government released the Drought Response, Resilience and Preparedness Plan.[129] This builds on decades of world-leading research and innovation from Australian policy makers and agricultural scientists.[130]

Multiple water management strategies have been attempted to address drought induced water insecurity. For example, in the Murray–Darling Basin of Australia, sophisticated water policy frameworks have been

established and reformed over the past two decades, including the National Water Initiative, the *Water Act*, the Murray–Darling Basin Plan, and 'the Basin Plan'.[81] However, these policy responses have been inadequate and will be increasingly limited in suitability as the climate warms. The prevailing primary challenge lies in devising optimal water governance decisions within an environment of escalating uncertainty surrounding adaptation pathways. These endeavours should be central to the revision of the *Water Act* and Basin Plan by 2026. Generally, national, multidisciplinary collaboration is essential to enhance water security in Australia, especially in resource-constrained areas.

Despite Australia's world-leading policy settings described above, for some high-risk rural communities, potential downturns in agriculture could be so substantial that farming may not be feasible.[87] Extreme levels of adaptation may be required as communities change the mixture of industries, perhaps involving exclusion of agriculture or moving away entirely. Drought resilience will remain challenging as the impacts of climate change continue. Therefore, some degree of government-provided drought support in Australia will be required in the long term.

Adaptation to climate-sensitive infectious diseases

Climate change has and will continue to cause more infectious disease transmission via affecting pathogen development, increasing vector growth rate, shortening the extrinsic incubation period, and changing human behaviour,[131–135] which leads to both spatial and temporal expansion of infectious disease cases. Many studies suggest that climate change with increased temperatures is causing more food-, water- and vector-borne disease cases in Australia.[133,136–139]

Currently, both national and state/territory government in Australia have developed their climate change (and health) adaptation plans to lay the foundations for dealing with food- and vector-borne disease issues. In Victoria, the Health and Human Service Climate Change Adaptation Action Plan 2022–2026 outlines a range of existing actions in relation to climate change and food-, water- and vector-borne diseases which will be strengthened by greater health and cross-sectoral engagement and an improved evidence base.[140] Similarly, in a conceptual framework for climate change, health and wellbeing in NSW, food- and vector-borne diseases have also been recognised as important health outcomes from climate change and are listed as one of the response policies.[141] In Queensland, Ross River virus infections and Dengue fever have been a particular focus of the state's climate change adaptation plans.[142] Western Australia's climate change health adaptation strategy emphasises that both food- and vector-borne diseases will be increased in the context of climate change and relevant actions are needed.[143] Climate change action strategies with have also been developed in South Australia, Tasmania, Northern Territory and ACT, mentioning some adaptation strategies addressing climate-sensitive infectious diseases (Supplementary Table S1). However, the state/territory-level strategies could be strengthened if better evidence were available to improve direct action on climate-sensitive infectious diseases.

Collaborative relationships will become increasingly important with the increase in diseases around the world. National, state/territory and local governments will need to amplify their joint work to prevent the arrival of exotic diseases or exotic vectors and prevent their spread across the country. This will be particularly important as the environment changes and disease vectors such as mosquitos move further south in Australia.[142] The Australian federal government is currently establishing a national CDC, similar to that in the United States. This provides an opportunity for a nationally consistent approach to emerging risks from infectious diseases due to climate change.[19] The theme of Biosecurity and Emerging Infections in the HEAL network[27] will help to develop a climate-informed early warning system based on One Health approach and provide more effective control strategies for climate-sensitive infectious diseases.[144]

Another important indicator for adaptation to climate-sensitive infectious disease will be in the capacity and capability of local healthcare workforce. To date, no state or territory has produced a specific action plan for infectious disease control and prevention such as improving communicable disease notification quality in light of climate change.

The development of a climate-informed Early Warning System constitutes an innovative and invaluable tool for more effectively controlling outbreaks of climate-sensitive infectious diseases.[145,146] Incorporating additional predictive factors such as socioenvironmental factors and web-based search query data into such an early warning system can help better predict climate-sensitive infectious disease transmission at finer spatial and temporal scales.[147] Such a system should be integrated with the *mHealth application with an artificial intelligence chatbot* to facilitate targeted early warnings and associated advisories to stakeholders and communities.[144,148] Based on the evidence generated from health risk assessments, some jurisdictions have developed and implemented climate-based early warning systems for food-borne/vector-borne diseases. In the Riverland region of South Australia, local councils have been working collaboratively with researchers for local vector monitoring so an early warning for possible Ross River virus infection could be issued.[149] However, more work is needed to evaluate, optimise and implement early warning systems.

Adaptation to the impacts of climate change on Indigenous health

There is a paucity of information about climate adaptation taken or suggested for urban, regional or remote

Indigenous communities.[150–153] Historically, plans and policies imposed on Indigenous communities have not been well received, and in relation to climate adaptation, any similar approach may constrain their adaptive capacity.[125,154–157] Participatory development approaches for adaptation strategies can be challenged by multiple stressors and uncertainty about causes of observed changes.[158,159] Adaptation planning would benefit from a robust typology[160] across the diversity of Indigenous life experience. Indigenous re-engagement with environmental management[161–163] can promote health[164,165] and may increase adaptive capacity, a range of programs being a significant component of this work.[166,167] As summarized in Supplementary Table S1, such programs include the Aboriginal-led Caring for Country land and sea management programs that focus on a more wholistic approach to 'people and country' wellbeing including mental health and physical health benefits of taking action to encourage adaptation activities to respond to the impacts of climate change on Indigenous Australians and the Country they manage. Adaptation activities that include seeking acknowledgement and restitution for loss and damage in some regions of Australia, for example in the Torres Strait, are currently being explored in the national arena. This approach comes after a successful international case brought to the United Nations Human Rights Committee which found that Australia's failure to adequately protect Torres Strait Islanders against adverse impacts of climate change violated their rights to enjoy their culture.

There is emerging interest in integrating Indigenous observations of climate change[168] and developing inter-cultural communication tools.[169] Extensive land ownership in northern and inland Australia and land management traditions mean that Indigenous people are well situated to provide greenhouse gas abatement and carbon sequestration services that may also support their livelihood aspirations.[170,171] Recent adaptations have included taking a very active role in the renewable energy transition. The First Nations Clean Energy Network is taking a pivotal role to ensure that Indigenous Australians are not left out or exploited in this new natural resource boom worth billions, and likely instrumental in financial and human resource opportunities for Indigenous Australians in the near term.

Communication and policy recommendations

Australia is at a critical juncture in terms of its response to the current and increasing threat of climate change. Despite the recent inquiries, such as the Royal Commission into National Natural Disaster Arrangements, in response to extreme climate events, Australia's health systems remain inadequate to the scale and urgency of the threat to human health. There is a clear and urgent need for a comprehensive collaborative approach across the whole of society and at all levels of local, state and national government to prevent, mitigate and adapt to the health impacts of climate change.

Working alongside communities should be fundamental to Australia's response, including a better understanding of the needs and risks of specific communities, particularly those most susceptible to climate effects and to assist with the development of equitable responses. So too, is increased awareness and education of the diverse strengths and knowledge that communities, especially those of First Nations Peoples, can bring to the climate change adaptation and to the management of climate-related risks through effective preventive, preparedness, response and recovery measures.

There are some signs of progress towards adaptation in the health sector, such as the development of a National Climate and Health Strategy, and the opportunity it provides to intensify action.[172] States and Territories are independently developing their own plans, but to achieve the greatest impact across Australia, these plans should link back to the national plan and be tailored as appropriate to the local context.[173–175] However, existing adaptation plans and strategies remain limited and are often untargeted, primarily due to current limited understanding of the mechanisms by which climate change and environmental extremes affect health, as well as the lack of evidence-based cost-effective specific adaptation measures. Therefore, more studies are warranted to understand the mechanisms and to develop and evaluate cost-effective adaptation measures.

Furthermore, Australia should commit to the World Health Organization's Alliance for Transformative Action on Climate and Health[176] and enhance the National Disaster Risk Reduction Framework to meet the vision of the Sendai Framework 2015–2030. Australia's proposed new National CDC is also an opportunity to take abroad approach to the assessment and management of all public health risks, including diseases that are sensitive to climatic factors.

Five areas for intensified policy responses at national, state/territory, and local levels are recommended:

1. Health Knowledge and Information Systems:
   - Enhance and strengthen data collection and analysis systems to monitor climate-related changes in population exposures, vulnerabilities and health outcomes and apply this information to drive effective actions.
   - Establish a dedicated climate health resilience research fund to further develop the evidence base for effective adaptation interventions that work in practice and enable sharing and scaling.
   - Weave together western and Indigenous knowledge systems including establishing equitable power relationships and co-governance arrangements; building respectful and trusting

partnerships; centering and leveraging Indigenous knowledge; and appropriate intellectual and cultural protections.

2. Workforce:
   - Increase the size, diversity and preparedness of the health workforce so that there are sufficient numbers to work with communities and stakeholders to reduce risks and cope with climate-related impacts on availability of workforce and surges in demand for their services, especially primary and community healthcare staff.
   - Upskill the health workforce through close collaboration between health and education agencies, universities and professional bodies to be able to assess, plan, communicate and respond to health risks related to climate change.
3. Critical infrastructure, including health services and supply chains:
   - Assess current and future climate-related risks to existing and planned health service buildings, hospitals and other facilities, and supply chains, improve structural and non-structural safety, and develop and exercise business continuity plans that incorporate compound and cascading extreme events.
   - Ensure that climate adaptation strategies consider critical infrastructure failure (e.g., power, drinking water, communications) and mitigate risks to population health, particularly for those most susceptible to harm or less able to respond.
   - Strengthen personal, household and business resilience strategies and plans in the event of critical infrastructure failure.
4. Service delivery:
   - Enhance existing emergency planning, response and communication activities to incorporate a greater focus on disaster risk reduction (as well as health protective behaviours during emergencies), cultural safety and intersectoral work to increase individual, community and neighbourhood resilience.
   - Support all healthcare systems to undertake vulnerability and adaptation assessments (VAAs), including remote and rural communities; embed VAAs within healthcare system management, accreditation and performance measures.
   - Ensure health service organisations develop adaptation plans including the use of climate information services to plan for staff and patient access barriers, and surges in demand, as a result of climate-related events.
   - Work with other sectors to develop long term climate and health resilience strategies at building, neighbourhood and community level (such as built environment interventions to promote urban cooling).
5. Financing:
   - Ensure that adequate financing is made available to increase resilience to the health impacts of climate change in Australia.
   - Ensure the health impacts for current and future generations are fully accounted for in investment decisions by incorporating comprehensive assessments of short and long-term health impacts in economic evaluations of the impact of climate-related events and the investments in climate risk management actions.

Meanwhile, effective climate change adaptation strategies require investments in the combination of preventive measures and capacities to prepare for, respond to and recover from climate-related extreme events. Particularly, it is important to keep a balance between preventive measures (e.g., urban planning, building code) and emergency response measures (e.g., climate disaster response plans), because the former is often overlooked compared with the latter in Australia's existing adaptation strategies mentioned in section Climate change adaptation measures and activities in Australia.

In section Key climate-sensitive health risk factors, we found that individuals with socioeconomic disadvantages (e.g., the elderly, the urban poor, those living alone, and people with limited access to health services or infrastructures) are often more likely to suffer from higher risks of adverse health effects of climate-related environmental extremes. It is imperative that all actors in health systems, including policymakers and health workers, collaborate with other sectors on addressing the determinants of health and enable access and availability of services to underserved groups who often live in vulnerable settings and face inequities that pose barriers to their ability to cope with the risks and impacts of a changing climate.

However, climate adaptation policies and strategies, if not implemented correctly and equitably, sometimes can have distributional impacts that benefit different groups disproportionately, potentially further exacerbating the vulnerability of disadvantaged individuals. For instance, constructing levees to manage floods can safeguard high-value properties while exacerbating floods in areas with lower property values. Building codes aimed at mitigating climate change may escalate housing costs, disproportionately impacting economically disadvantaged individuals. The creation of green spaces to mitigate urban heat may disproportionately benefit affluent neighborhoods unless a framework for equitable planning is rigorously integrated. To promote equity and justice, climate adaptation policies and strategies should be implemented in an equitable manner and ensure the welfare of disadvantaged populations.[177]

Contributors

Yuming Guo and Shanshan Li were Team co-leaders. Rongbin Xu is the Project Coordinator. Rongbin Xu and Karin Leder made significant edits to the manuscript. All the other authors contributed to writing the original draft. All authors contributed to writing-review & editing.

Editor note

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Appendix A. Supplementary data

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