ANNUAL REVIEWS

Annual Review of Public Health

Public Health Preparedness for Extreme Heat Events

Jeremy J. Hess,[1,2,3,4] Nicole A. Errett,[2,4,5] Glenn McGregor,[6,7] Tania Busch Isaksen,[2,4] Zachary S. Wettstein,[1,4] Stefan K. Wheat,[1,4] and Kristie L. Ebi[2,3,4]

[1]Department of Emergency Medicine, School of Medicine, University of Washington, Seattle, Washington, USA; email: jjhess@uw.edu

[2]Department of Environmental and Occupational Health Sciences, School of Public Health, University of Washington, Seattle, Washington, USA

[3]Department of Global Health, School of Medicine and School of Public Health, University of Washington, Seattle, Washington, USA

[4]Center for Health and the Global Environment (CHanGE), University of Washington, Seattle, Washington, USA

[5]Department of Health Systems and Population Health, School of Public Health, University of Washington, Seattle, Washington, USA

[6]Department of Geography, Durham University, Durham, United Kingdom

[7]Ustinov College, Durham University, Durham, United Kingdom

Annu. Rev. Public Health 2023. 44:301–21

First published as a Review in Advance on January 6, 2023

The *Annual Review of Public Health* is online at publhealth.annualreviews.org

https://doi.org/10.1146/annurev-publhealth-071421-025508

Keywords

extreme heat event, heat action plan, climate change, disaster risk reduction

Abstract

Heat is a dangerous hazard that causes acute heat illness, chronic disease exacerbations, adverse pregnancy outcomes, and a range of injuries. Risks are highest during extreme heat events (EHEs), which challenge the capacity of health systems and other critical infrastructure. EHEs are becoming more frequent and severe, and climate change is driving an increasing proportion of heat-related mortality, necessitating more investment in health protection. Climate-resilient health systems are better positioned for EHEs, and EHE preparedness is a form of disaster risk reduction. Preparedness activities commonly take the form of heat action plans (HAPs), with many examples at various administrative scales. HAP activities can be divided into primary prevention, most important in the pre-event phase; secondary prevention, key to risk reduction early in an EHE;

and tertiary prevention, important later in the event phase. After-action reports and other postevent evaluation activities are central to adaptive management of this climate-sensitive hazard.

EXTREME HEAT EVENTS AND POPULATION HEALTH

Extreme heat events (EHEs), commonly known as heat waves, are periods of abnormally high ambient temperatures. The hazard of extreme heat has always garnered significant attention given its potential to cause significant morbidity and mortality, even with exposure periods of no more than a day. In recent years, temperature distributions have shifted due to climate change, and EHEs have become both more frequent and more severe. EHEs of varying intensity have occurred regularly around the globe in the last two decades, causing significant adverse health impacts. While there has been some adaptation by health and other authorities to this shifting risk, the population health impacts of EHEs are increasing. Public health systems must prepare for EHEs, as each summer brings the possibility of significant heat-related impacts from a changing climate.

Here we begin by characterizing the relationship between EHEs and population health; explaining the rationale for focusing specifically on EHEs; and describing the impact of climate change on EHE frequency and severity, including the emerging use of climate change attribution science. We further consider how EHE preparedness and heat action plan (HAP) development and administration are exemplary activities of climate-resilient health systems; outline how HAP activities are a function of disaster risk reduction; enumerate the key HAP activities in EHE pre-event, event, and postevent phases and how they relate to primary, secondary, and tertiary prevention; and explore considerations related to HAP implementation and evaluation.

The overarching goal of this review is to provide practitioners with information regarding the rationale for prioritizing EHE preparedness and HAP development as the climate changes; to highlight extant resources to support HAP development, administration, and review; to highlight important overlaps with disaster risk reduction efforts; and to identify and prioritize opportunities for learning related to EHE preparedness and HAP development and administration.

Definitions of Extreme Heat Events and Heat-Related Illness

There are no universal definitions for EHEs or heat-related illnesses (HRIs), so we begin with a brief review.

Extreme heat events. While there is no universal definition for what constitutes a heat wave or EHE, there is significant conceptual overlap in content referring to a period of sustained, uncomfortably hot weather. Most definitions reference an intensity and/or duration threshold that varies from one to five days. For example, the American Meteorological Society defines a heat wave as "a period of abnormally and uncomfortably hot and usually humid weather" (**https://glossary.ametsoc.org/wiki/Heat_wave**); the National Oceanic and Atmospheric Administration (94) in the United States defines a heat wave as "a period of unusually hot weather that typically lasts two or more days. The temperatures have to be outside the historical averages for a given area." The Intergovernmental Panel on Climate Change (IPCC) (86) defines a heat wave as "a period of abnormally hot weather," and the World Meteorological Organization (145) defines a heat wave as "a period of abnormally and uncomfortably hot weather."

Heat-related illness. Extreme heat has long been recognized as an important environmental exposure with the potential to upset the body's homeostatic thermal balance. Core temperature is maintained within a narrow range via multiple behavioral and physiological mechanisms (40). An overwhelming heat load, whether exogenous, endogenous, or in combination, upsets this balance (88) and can lead to a suite of acute heat illnesses, exacerbations of chronic disease (16, 125), and other adverse health outcomes. HRIs are adverse health impacts associated with heat exposure and can be subdivided into four categories: acute heat illnesses, chronic disease exacerbations, pregnancy complications, and behavioral and other emergencies associated with extreme heat exposure. We elaborate on each category in the following section.

Epidemiology of Heat-Related Illness

Striking rates of mortality have been observed in historical EHEs (79), such as in Europe in 2003 (109) and Chicago in 1995 (142). Recent evidence has found significant mortality associated with heat exposure around the globe; studies from Turkey (22), Korea (124), China (148), Russia (8), and the US Pacific Northwest (6, 60) illustrate its global impact. Reported heat-related fatalities are likely a vast underestimate of the true burden due to limitations in reporting and case attribution (137).

Susceptible populations. While extreme heat exposure, left unmitigated, is a risk for all, some populations are at increased risk due to physiological, behavioral, or disproportionate exposure-related factors. These populations typically include (76) the elderly (11, 68), particularly those with multiple medical comorbidities (122, 147); pregnant individuals (113); people of color experiencing the heat-related effects of systemic racism (80, 98, 119); those suffering from homelessness (62); outdoor workers (108, 126); children and infants (26); and those with lower educational attainment (31, 98). Males have also been identified as being at increased risk of HRI, likely resulting from behavioral and psychological factors as opposed to physiological factors for other vulnerable groups (50).

Acute heat illnesses. Many HRI result from disruption to the thermoregulatory mechanisms in high environmental heat exposure settings. Corporal heat production results from metabolism and exertion and, under normal conditions, heat removal is accomplished through radiation, convection, conduction, and evaporative cooling (64). When heat loads are excessive, the body's ability to remove excess heat is reduced, core temperature increases, and HRI can occur.

The spectrum of acute HRI is broad, including mild disease such as heat cramps and edema, moderate disease such as heat syncope and heat exhaustion, and, at the most extreme and life-threatening, heat stroke (78). Heat cramps and edema are benign, self-limiting conditions that are not well documented during EHEs, likely given affected individuals' limited contact with the health care system. Heat syncope is a brief episode of dizziness or loss of consciousness resulting from heat exposure, often in the setting of positional changes or prolonged standing (30). Heat-related vasodilation and dehydration, along with pooling of blood in the venous system, result in decreased blood pressure and cerebral blood flow and the symptoms of light-headedness or syncope. The symptoms typically resolve with rest, cooling, and rehydration. Heat exhaustion is the most common HRI and can progress to heat stroke if not identified early and treatment initiated (49). Similar to heat syncope, heat exhaustion may include symptoms of dizziness or syncope but is also characterized by weakness, intense thirst, and gastrointestinal symptoms, as well as dehydration and sodium losses during heat exposure (49). Heat stroke is the most severe HRI, including many of the symptoms of heat exhaustion but characterized by hyperthermia, with a core temperature greater than 40°C, and neurological impairment, such as confusion, seizure, or coma (16, 49). Above this temperature threshold, thermoregulation processes are severely impaired, critical proteins denature, and an inflammatory response similar to sepsis ensues, leading to multiorgan failure and death if untreated (78). Patients who survive heat stroke are at increased risk of subsequent mortality from other causes (33, 135).

Chronic disease exacerbations. Heat exposure can also exacerbate multiple chronic diseases. Most notably, heat-related exacerbations of cardiovascular disease (120), respiratory disease (4), and kidney injury and failure (73) have been observed and contribute to EHE mortality (60). In many EHEs, chronic disease exacerbations commonly outnumber acute heat illnesses (61, 73, 76). Risk factors include preexisting cardiovascular, pulmonary, renal, neurologic, and psychiatric disease. Use of medications, such as diuretics and psychotropic medications, in addition to alcohol and drug use, impacts water and electrolyte balance and affects thermoregulation (77). Strenuous outdoor exercise and labor also increase the risk (49).

Pregnancy complications. EHEs present a number of potential risks to pregnant people, embryos, and fetuses. Pregnancy, wherein a large proportion of the circulating blood volume is directed to the fetus, can compromise compensatory circulatory responses, constrain maternal heat shedding, and threaten the fetus with constrained blood flow to the placenta (107, 115). A number of adverse fetal and neonatal outcomes have been identified, including preterm delivery, stillbirth, low birth weight (26, 151), preeclampsia and other hypertensive disorders of pregnancy (54), gestational diabetes (99), and pregnancy-related emergency hospital admissions (70). Investigations of these associations and the magnitude of associated risks and how to improve pregnancy-related health protections are ongoing (111).

Injuries. Heat exposure is associated with a number of behavioral changes that can increase risk for heat-related injuries. Drowning is a prime example. People often seek water to cool off in hot weather, as areas next to bodies of water are typically cooler and provide ways to cool off through immersion. Water exposure can be dangerous for those who cannot swim, however, particularly children; this association underlies the strong association between ambient air and water temperature and drowning rates (15, 18).

There is a weaker but nevertheless impactful association between ambient temperature and violence (128), hypothesized to be associated with general discomfort associated with higher temperatures and with drops in circulating serotonin levels (150) and increased levels of testosterone (3). Lower levels of serotonin increase the prevalence of depressive mood and anxiety, while increased testosterone levels are associated with more aggressive behavior, observed in higher rates of intimate partner violence (117) and more violent crimes during summer periods, with associated increases in injuries.

Temperature Distributions and Population Health Risks

Population health status is attuned to and affected by local climate. In the vast majority of settings where associations between health outcomes like mortality have been associated with ambient temperature, there is a "J," "U," or hockey stick–shaped curve, with a minimum mortality temperature (MMT), typically in the 70th to 80th percentile range (48, 58). The MMT is also sometimes referred to as the theoretical minimum risk exposure level. In most cases, the relative risk of adverse health impacts increases monotonically above the MMT, with dramatic increases at the upper end of the exposure spectrum (48, 58) (see **Figure 1**).

When we apply the conceptual definition of EHE to these distributions, it is immediately apparent that EHEs refer solely to the upper end of this theoretical curve. It is also apparent that the burden of disease associated with temperatures above the MMT but below the EHE threshold is higher than the burden associated with EHEs alone. Last, it is clear that risks, in terms of additional disease burden for each additional unit of warming, are highest at the upper end of

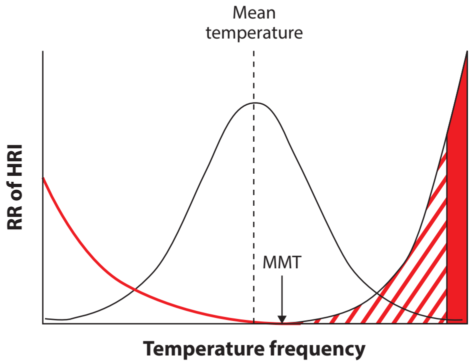

Figure 1

Temperature distribution, minimum mortality temperature, and risk of HRI (*red diagonal lines*), including subset of HRI associated with EHEs (*solid red area*). Abbreviations: EHE, extreme heat events; HRI, heat-related illness; MMT, minimum mortality temperature; RR, relative risk.

the exposure range. In short, at the upper end of the HRI curve, risk increases more dramatically than at any other point, but exposures at this end of the curve are by definition rare. EHEs garner disproportionate attention given their significant and highly visible impact on population health. However, to have the greatest public health impact, interventions to reduce risks in EHEs will also reduce risks when temperatures are still dangerous but less extreme.

Rationale for Prioritizing Extreme Heat Events

While risk is increased above MMT, there are nevertheless multiple reasons to prioritize specific preparedness and response efforts associated with EHEs. By virtue of their intensity, EHEs increase the likelihood of failures across a wide range of systems that are important to health protection (127). EHEs pose increased risk to electricity generation and transmission, cooling systems and equipment required for health care delivery, and infrastructure used for transportation and other essential systems. EHEs, which are typically regional, can put large areas at risk and limit opportunities for mutual aid. In many cases, EHEs experienced in recent years have occurred in conjunction with other hazards, including droughts, wildfires, and infectious diseases (5). The increased likelihood of multisystem failures with the potential to affect systems essential to health protection is an important reason for prioritizing EHEs in public health preparedness efforts (2).

CLIMATE CHANGE AND EXTREME HEAT EVENTS

Anthropogenic activities, primarily the release of carbon dioxide from burning of oil, gas, and coal, are adding energy to the climate system, increasing the frequency, intensity, and duration of heat waves (85). The latest IPCC assessment concluded that it is virtually certain that since the 1950s, EHEs have become more frequent and intense over most land regions (5). The observed average climate forcing increased from 0.50 watts per meter squared for the period 1971–2006 to 0.79 for the period 2006–2018 (5).

Health Impacts of Heat Exposure Driven by Climate Change

Increases in the extent and rate of warming are affecting human health and well-being. In 2020, children under one year of age were exposed to 645 million more person-days of exposure to heat wave days, while adults over 65 years of age were exposed to 3.1 billion more person-days of exposure, relative to a 1986–2005 baseline (110). These findings translate into an average of 4.6 more heat days per person for older adults and 4.1 more days for children. There has been a steady increase in exposure to heat days since 1980. Heat-related mortality in people over the age of 65 years increased between 2018 and 2019 in all World Health Organization (WHO) regions except for Europe.

EHE exposure has additional societal costs such as lost productivity and impacts to mental health and wellness. Worldwide, 295 billion potential work hours were lost in 2020, or 88 work hours per employed person. Pakistan, Bangladesh, and India experienced the greatest losses, particularly among agricultural workers (110). Using data from geolocated tweets and climate data from 2015 and 2020, local heat wave exposure significantly increased negative mental health sentiment and reduced positive expressions (110).

Detection and Attribution of Climate Change Influence on Extreme Heat

Using a formal statistical analytic method termed detection and attribution (42), multiple recent EHEs were assessed to be extremely unlikely without climate change (5). Recent examples include the 2022 heat wave in the United Kingdom, which would have been extremely unlikely without climate change (146); the heat wave in India and Pakistan that started in March 2022, which was 30 times more likely with climate change (149); and the June–July 2021 heat dome in northwestern North America, which was virtually impossible without climate change (104).

Detection and attribution methods are furthermore being applied to quantify the extent to which anthropogenic climate change is causing heat-related mortality. For example, the Northwest North America heat dome directly caused at least 619 heat-related excess deaths in British Columbia (9). The same heat dome resulted in a 69-fold increase in heat-related emergency service calls in the states of Alaska, Idaho, Oregon, and Washington (118). Other researchers have looked at the attributable heat-risk burden over time and have found similar climate fingerprints. Vicedo-Cabrera et al. (134) used mortality data from more than 700 locations to estimate mortality burdens associated with additional heat exposure resulting from warming over the period 1991–2018. Research spanning 43 countries found that 37.0% (20.5–76.3%) of the heat-related deaths during summer months were attributed to anthropogenic climate change. The burdens varied geographically, with only one location from Africa (134).

Projections indicate that every additional increment of warming results in larger changes in the frequency and intensity of heat events, leading to greater exceedances of extreme heat thresholds (5). A synthesis of projected changes in heat-related mortality concluded that recent warming increased risks from undetectable, where it was not possible scientifically to determine whether climate change had changed heat-related mortality, to moderate, where there was at least medium confidence that climate change was causing heat-related mortality (39).

Additional warming is projected to increase risks across the century; the extent of additional risk will depend on the extent to which greenhouse gas emissions are reduced over the next decade and on the extent to which health systems are strengthened to be climate-resilient and environmentally sustainable. Immediate and significant investments in adaptation and mitigation would slow and reduce but not eliminate increases in heat-related morbidity and mortality.

CLIMATE-RESILIENT HEALTH SYSTEMS

EHEs pose risks to public health and health care delivery systems. The WHO has published guidance for building climate-resilient health systems and climate-resilient and environmentally sustainable health care facilities (143, 144). The WHO (143) defines a climate-resilient health system as "one that is capable to anticipate, respond to, cope with, recover from, and adapt to climate-related shocks and stresses, so as to bring sustained improvements in population health, despite an unstable climate" (p. 8). To be climate-resilient, each building block of health systems at local to national scales also needs to be climate-resilient: leadership and governance, health workforce, health information systems, essential medical products and technologies, service delivery, and financing. These building blocks come together to build resilience by reducing vulnerabilities and inequities and providing universal access to essential services, including health, education, safe water, and adequate nutrient-dense food in the context of managing an uncertain future (143). In addition, coordination and collaboration are required with health-determining sectors, including water, energy, agriculture, and urban planning, to ensure that their adaptation and mitigation actions protect and promote health and well-being.

Proactive and effective management of heat-related morbidity and mortality requires addressing each health system building block. Developing HAPs, which describe heat wave early warning and response systems and long-term planning for a warmer future, is an important policy action requiring leadership and attention to governance. As examined below, HAPs also require investments in several other areas of climate-resilient health systems, including surveillance, communications, and research.

Health care facilities need to be prepared not only for an influx of patients suffering from heat stress and worse, but also for EHEs to affect their own operations when, for example, brownouts reduce electricity for critical equipment. Both health services and health care facilities could benefit from conducting stress tests of their ability to effectively function during EHEs outside the range of recent experience (38). Stress tests should include representatives of all entities involved in HAPs, not just representatives of critical functions, to identify critical points where overwhelming one service could cascade throughout the collaborative network underlying the plan, compounding risks.

Health information systems are beginning to incorporate iterative adaptive management into managing the burden of climate-sensitive health outcomes, recognizing that climate change will do more than just exacerbate current weather-related hazards (36, 57). Adaptive management is a structured and iterative process of decision-making in the face of deep uncertainties about the magnitude and pattern of climate change and of societal responses to prepare for and manage a changing climate. Elements of adaptive management include a strong emphasis on stakeholder engagement and on ensuring that any actions taken focus on reducing inequities and protecting the most vulnerable. Systems-based approaches directly consider that climate change is affecting all aspects of society, leading to compounding and cascading risks, such as EHEs reducing agricultural yields and increasing food insecurity. Adaptive management, including institutional learning, recognizes that climate change may overwhelm the adaptive capacity of health systems, as it has in several EHEs.

A critical component of strengthening health information systems is modifying monitoring and surveillance programs to provide accurate and timely health and environmental data relevant for managing changes in the burden of climate-sensitive health outcomes (41). A challenge for the United States is that hospitalization and mortality data are not available for many months until after an event, potentially resulting in less effective responses. In some cases, surveillance is more rapid: The Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE), originally designed as a way to detect and track infectious disease in communities, has been quickly leveraged to conduct surveillance around natural hazards including EHEs (19).

There are multiple opportunities for developing and deploying medical products and technologies to increase the effectiveness of adaptation and strengthen health systems. For example, exposure to high ambient temperatures can increase heat stress in outdoor workers, leading to increased health impacts and reduced worker productivity. New technologies are being developed for personal exposure. For example, about one-quarter of studies of the effectiveness of wearables in detecting direct health impacts and individual exposure during heat waves concluded that wearables are valid and reliable for measuring health parameters (74). Knowing when individuals begin to experience heat stress provides opportunities for faster interventions to reduce and hopefully eliminate heat stroke and mortality.

Supporting these health system activities requires human and financial resources, which have mostly been lacking. Exceptions in the United States include support for state and local health departments from the Centers for Disease Control and Prevention program on Building Resilience to Climate Effects (BRACE) (81). The BRACE program enables public health agencies to assess and use robust science to project changes in climate-sensitive health burdens under different scenarios, prioritize adaptation options, and facilitate institutional learning. BRACE reinforces the long-established commitment of health systems to developing and implementing evidence-based interventions, though the program funds only a small proportion of the need.

DISASTER RISK REDUCTION APPLIED TO EXTREME HEAT EVENTS

Disaster risk is widely recognized "as the consequence of the interaction between a hazard and the characteristics that make people and places vulnerable and exposed" (133). EHEs are events in which temperature extremes, potentially coupled with infrastructure failures, increase the likelihood of disastrous impacts (101). Many climate and health interventions, defined by Conlon & Austin (27) as "actions which aim to disrupt a climate-sensitive exposure from impacting a health outcome, or actions which develop capacity to respond to climate-sensitive health effects," are thus also disaster risk reduction activities. Disaster risk management, or policies and strategies aimed at reducing risk and strengthening adaptive capacity, can help prepare jurisdictions for EHEs (132), often in the form of HAPs.

Overview of Heat Action Plans

As noted above, HAPs are policy documents that outline strategies a jurisdiction plans to take before, during, and after an EHE to reduce morbidity and mortality from EHEs (75). HAPs may be standalone or appended to a jurisdiction's emergency operations plan or equivalent (1), where "the scope of preparedness and emergency management activities necessary for that jurisdiction" are defined (45, p. 3-1).

HAPs have been developed at the national and subnational levels (72, 82). Notwithstanding their various flavors (25, 84, 87) and their scale dependency in terms of detail (53, 56, 123, 138), HAPs have emerged as an all-encompassing approach to managing heat risk from the individual level to the population level, with the aspiration to integrate both short- and long-term EHE preparedness and response (53, 84). Clear governance of heat as a hazard with the identification of an agency to provide HAP leadership and coordination is essential (37). HAPs typically contain a heat warning system and a description of public health interventions (75). A heat warning system includes

> weather forecasts of high temperatures that may also include humidity; a method for assessing how future weather patterns may evolve in terms of a range of health outcomes; the determination of heat-stress thresholds for action; and a system of graded alerts/actions for communication to the general population or specific target groups about an impending period of heat and its intensity and to government agencies about the possible severity of health impacts. (87, p. xi)

Public health interventions include surveillance, heat health messaging and communications, social care and frontline health, neighbor outreach, cooling centers, water bottle distribution, fan distribution and use, energy assistance, changes to the built environment, and/or workplace heat alerts (1). Communication and education initiatives, longer-term preventive measures, and a climate-resilient health system are wrapped around these core more event-oriented interventions (64).

HAPs include a mix of primary (reducing hazard severity and limiting exposure), secondary (limiting disease development in exposed people), and tertiary (limiting disease progression and palliating symptoms) prevention activities. In this framework, primary prevention maps roughly to pre-EHE activities, while secondary and tertiary prevention activities are more often deployed during an EHE. It is important to note, however, that HAPs are always active and engaging in different types of prevention, though the mix will vary by risk level. For instance, in the United Kingdom's HAP, action levels include long-term planning, heat wave and summer preparedness, heat wave in forecast, heat wave action, and major incident emergency response (105).

Primary Prevention and Pre-Event Activities

HAPs often include primary prevention efforts focused on climate-sensitive urban design and planning. A wide range of passive and active cooling technologies—using evaporative urban greening, ground cooling, enhanced surface reflectivity (albedo), and ventilation approaches in addition to nature-based solutions—are available (65, 116, 136). For example, discernible temperature reductions can be achieved at the neighborhood scale using a mixture of greening, irrigation, and various albedo configurations (63). To achieve significant heat mitigation, however, many modifications need to be applied at scale. Green roofs are a good case in point; although these building features can achieve roof surface temperature reductions of ~20°C, little benefit is achieved beyond the immediate vicinity of the roof (29). Furthermore, many approaches that obtain significant urban heat mitigation rely heavily on access to water for irrigation and green/blue infrastructure maintenance (17), which may prove to be unsustainable during EHEs due to water limitations and associated increased costs (141).

Pre-event activities also include efforts to support HAP administration. These activities span a range of activities from epidemiological analysis in service of developing warning thresholds to standard disaster response activities, including development of incident command structures.

Secondary Prevention and Early Event Activities

Secondary prevention in HAPs is focused on identifying EHEs and communicating risks so that people can prepare and respond appropriately. Secondary prevention also includes a suite of behavioral interventions to facilitate cooling and reduce the likelihood that a patient will decompensate from heat exposure. Several strategies leverage evaporative and conductive cooling strategies, including using electric fans, with and without misting; self-dousing; wearing wet shirts; immersing feet; and applying ice towels (64). There has been variable guidance regarding the use of electric fans for cooling and the potential risk of dehydration, particularly in elders (64).

Health system preparedness is important to both secondary and tertiary prevention and is an essential HAP element. Preparedness should include (*a*) training to diagnose and treat heat-related illness, (*b*) appropriate staffing of prehospital and hospital-based emergency care services, and (*c*) provision of resources needed to manage patients with acute hyperthermia (79). Facility capacity to maintain operations during periods of extreme heat and high patient care demand should be assessed (24, 102). Health systems should also not underestimate the overall increased demand for patient care; demand above baseline can vary depending on the geographical area. While some studies have reported a 3% increase in service utilization above base volume, driven particularly by renal and respiratory disease exacerbations (52, 73), others have found significantly higher increases in health care utilization (up to 14%) and an expanded list of health outcomes (20, 32, 52, 73).

Public health practitioners and supporting partners play a critical role in primary prevention during EHEs by increasing access to cooling shelters, by facilitating heat-health warning systems, and by distributing heat vulnerability information among other activities (97). These activities should involve community-based collaborations and location-specific heat response plans that are culturally appropriate for those at highest risk (55).

Tertiary Prevention and Event Activities

Tertiary prevention in HAPs focuses on supporting HRI management, most of which occurs in a clinical context. Ideally, response activities during an EHE have been planned in advance through HAP development and practiced through table-top exercises or drills.

Emergency medical services (EMS) are an important gateway and therefore represent an important pressure point when considering system capacity during an EHE (100). Prehospital providers have direct insight into the safety conditions of patients in the home, referred to as situated practice. Through this unique insight, EMS providers may assess a patient's lived environment and provide resources and expertise for how to mitigate the risk of heat and, under appropriate medical direction, obviate the need for hospital transport (96).

In both the prehospital and hospital environments, rapid recognition and aggressive early treatment of HRI are essential. In general, tertiary prevention of acute heat illness is focused on rapid diagnosis and intervention to reverse symptoms and to reduce core temperature (43) at a rate greater than 0.15°C per minute (47). Tertiary prevention activities also include efforts to maintain operations of EMS systems, hospitals, clinics, and other elements of health care delivery. Thus, the development and integration of evidence-based clinical best practices for managing HRIs such as heat stroke should be considered a priority to improve early diagnosis and resource mobilization (112). Furthermore, as the risk of HRI and other climate-sensitive health outcomes increases, so too will the demand for a climate-ready workforce that is both adaptable and knowledgeable about EHE-related risks and how to address these risks in clinical encounters (114). This adaptation may entail adjusting facility-level surge plans to ensure preparedness for sudden increases in patient load, utility outage plans, and improvement of interfacility mutual aid strategies (7).

Finally, additional attention should be paid to special populations, including psychiatric patient populations. Heat stress resulting in increased demand for acute psychiatric care may stress the already misaligned relationship between demand and need for psychiatric beds and thereby further strain the capacity of acute care facilities during an EHE (95, 121). Health care systems should therefore establish preparedness frameworks accounting for special populations to ensure sustained health care service delivery.

Post-Event Activities and After-Action Reviews

There is limited evidence to support the practice of public health emergency preparedness and response broadly (23, 21, 69), and EHE preparedness and response is no exception. While HAPs have been shown to reduce heat-related morbidity and mortality (12, 55, 129), the effectiveness of specific strategies or interventions remains elusive (35, 106). Bidirectional communication between researchers and those responsible for HAP development and implementation has been called for to inform targeted research that responds to practitioner information needs, with cascading impacts to morbidity and mortality reduction following EHEs (37).

Postevent activities, specifically surveillance and after-action reviews (AARs), can inform organizational learning about the implementation and effectiveness of an organization's response and identify opportunities for improvement. While surveillance conducted during an event, largely focused on morbidity, can inform activation and targeting of public health interventions, surveillance must necessarily continue long after temperatures drop to account for both short-term lags in morbidity and longer-term lags in mortality. Italy's national heat health protection program, developed in 2004 by the Italian Department for Civil Protection and the Ministry of Health, integrates both peri-event surveillance, engaging clinicians and social workers, and postevent mortality surveillance to estimate the impacts of heat and EHEs (90). However, among 17 of 27 WHO European Region Member States that have a HAP and who were recently surveyed, only 24% reported full implementation of their HAP, while 29% reported partial implementation (83), demonstrating the need for additional integration of formal surveillance systems into HAPs globally.

AARs are commonly implemented following disasters and public health emergencies. AARs are qualitative assessments of actions taken during a response, including formal (e.g., large workshops led by trained facilitators) or informal (e.g., hotwashes or debriefings) collection opportunities, that seek to identify best practices, areas for improvement, and lessons learned (93). AARs are not external evaluations and do not measure performance against standards or benchmarks but seek to bring stakeholders together to achieve consensus on ways to improve preparedness and response (93). However, evidence suggests that AARs may be underutilized to inform organizational learning and improved capacity in the context of EHE response. Indeed, integration of formal monitoring and evaluation has largely evaded national-level HAPs, hampering the ability to identify cost-effective public health interventions (75). Moreover, none of the 42 after-action reports available from the 63 AARs supported by the WHO from 2016 to 2019 were completed in response to an EHE (28). Limited evidence at the subnational level also supports the need for additional attention to AARs and self-evaluation; only 7% of 176 counties from 30 US states that responded to a survey following EHEs in 2011 reported self-evaluation of their response (139).

AARs can support practice improvement in anticipation of future EHEs, and AARs conducted across multiple events can be compiled into a database to identify common areas for improvement (93). For example, based on lessons learned, HAPs can be rapidly modified to improve implementation. Moreover, other jurisdictional disaster risk management plans may be modified to facilitate reduction of health harms caused by EHEs based on lessons learned through AARs. For example, hazard mitigation plans, which assess disaster risks and outline long-term solutions to protect people and property (46), can support longer-term protective approaches such as increasing green space and other land use changes. A 2018 survey of state hazard mitigation officers found that the majority (85.7%) of 35 respondents reported integrating climate change into their state's hazard mitigation plans (51), highlighting an opportunity in this regard.

Increased attention and influxes of resources commonly follow public health emergencies and disasters, offering opportunities to build resilience through recovery and reconstruction (59, 131). Given the need for infrastructure changes, including increased green space, cool roofs, and updated building codes, to increase resilience against EHEs, recovery presents an opportunity to build both EHE and climate change resilience. However, a review of US state laws found that only 17 states have laws that explicitly assign public health agency responsibilities or authorities in disaster recovery (103); in addition, less than one-third of 33 assessed state-level disaster recovery plans explicitly mention health in the overall vision or goal of the plan nor are strategies outlined to address long-term health care or behavioral health needs (67). Accordingly, the health sector has a substantial opportunity to integrate more meaningfully into disaster recovery planning and preparedness, including by ensuring the linkage of disaster recovery plans with health improvement plans, climate action plans, and other long-term planning to create built environments that support health (59).

HEAT ACTION PLAN EVALUATION AND IMPLEMENTATION

Evaluation

Evaluation is essential not only to assessing the effectiveness of EHE preparedness but also to improving program quality and to achieving the goal of adaptive management of climate-sensitive health risks. Recognizing the need for evaluation and making provisions for evaluation activities are not as common as they should be in HAPs to date, however (75). The lower-than-expected prevalence of these activities is at least in part because evaluating EHE preparedness is challenging on multiple fronts. HAPs include a broad range of activities at multiple timescales, and HAPs across locations often emphasize different interventions based on local population health status, prevalent risk and protective factors, and other considerations (129, 130). Gathering adequate health outcome data is a perennial challenge, and developing methods that adequately allow for the assessment of causal relationships between interventions and risk reduction is difficult (35).

The evidence regarding HAP efficacy is mixed, in part as a result of these evaluation challenges, and it is difficult to draw strong causal inferences from the available data (35). Dwyer et al. (35) identified several challenges to effective evaluation, including accounting for confounding and effect modification, distinguishing and disentangling the effects of individual interventions applied in concert, establishing counterfactual scenarios, allowing for adequate follow-up periods and accounting for mortality displacement, maintaining a focus on mortality and reversing the neglect of morbidity outcomes, and improving the lack of comparability across outcomes and methods. The authors outlined several recommendations for HAP evaluations, which we include in **Table 1**, highlighting several relatively well-done studies with robust methods as examples (12, 13, 138).

Implementation

Research has demonstrated inconsistent adoption of EHE preparedness, response, and recovery activities. A 2011 survey of 190 local jurisdictions across 30 US states found that only 40% of counties had existing heat plans, with greater heat preparedness among those with plans compared to those without (139). The most common activities reported focused on communication, outreach, and interorganizational collaboration (139). These findings aligned with an assessment of heat response plans from 18 US cities with a history or risk of heat-related mortality conducted nine years earlier (in 2002), which found only one-third to have any written heat plans, including heat response measures integrated into all-hazards response plans, and a substantial proportion of standalone plans were found to have minimal specifics (14). At the national level, only 17 of

Table 1 Recommendations for improving HAP evaluations

Number	Summary of recommendations
1	Leverage natural experiments and prioritize use of quasi-experimental methods
2	Prioritize collection of data on possible alternative explanatory factors
3	Use incremental changes in HAP as opportunities to evaluate individual interventions
4	Use analytical techniques that can assess and account for mortality displacement and response time lag, including DLNM in time-series regression and ARIMA models
5	Prioritize collection of morbidity data, including leveraging partnerships where possible
6	Consider using the universal heat index (91, 92) in HAP design and evaluation
7	Publish and disseminate HAP evaluation findings

Table adapted from Dwyer et al. (35) (CC BY 4.0).
Abbreviations: ARIMA, autoregressive integrated moving average; DLNM, distributed lag nonlinear model; HAP, heat action plan.

27 WHO European region Member States that responded to a recent survey reported having a HAP (83). All Member States with a HAP reported some level of implementation of the following: "agreement on a lead body, accurate and timely alert systems, heat-related health information plans, strategies to reduce health exposure, and care for vulnerable groups" (83). Insufficient and erratic engagement in EHE preparedness aligns with the health sector's slow adoption of climate change and health programming more broadly (44).

Access to the benefits of HAPs may be inequitable; in other words, they may not reach the most at-risk populations. Without precise or targeted approaches to intervention delivery, these interventions may actually have limited effectiveness at scale. For example, an estimated 60,000–1.6 million people in the general public would need to access cooling centers in order to prevent one death (10). A recent study of cooling centers in 25 US cities found that adults over age 65 had less coverage than did their under age 65 counterparts, measured by cooling centers within a 0.8-km walking distance catchment area (71), pointing to a discordance between risk and risk management. Many jurisdictions face challenges identifying heat health risks, and production of vulnerability maps, such as those supported by the National Environmental Public Health Tracking Network (**https://ephtracking.cdc.gov**), has been proposed as a solution to this dilemma (101).

A variety of barriers may hinder jurisdictional engagement on EHE preparedness and response. A qualitative study of 73 interviews in 4 US jurisdictions found local context, political will, and resources to influence local-level engagement in EHE preparedness and response (140). A 2019 literature review identified several challenges related to heat planning more broadly, including planning silos and scales, necessary legal infrastructure, and the complexities of competing priorities and limited resources (66). A national survey of planning professionals across US cities found funding (and associated availability of time and staff) to be the most significant barrier of 12 barrier categories, followed closely by higher priorities, leadership, public support, expertise, knowledge of heat strategies, and coordination between agencies or jurisdictions (89). Key informant interviews with 17 health officials in the Pacific Northwest identified collaboration and partnerships; communication within, between, and across sectors; resources, capacity, and authority; focus on equity; leverage of all-hazards emergency preparedness and response capacity; and training as ways to support state and local health department engagement in climate change and health adaptation more broadly (34).

CONCLUSION

Heat, particularly when extreme, is a dangerous hazard; climate change is already increasing the frequency, intensity, and severity of EHEs for a number of regions across the globe. Given the significant population health impacts of EHEs, broader efforts to protect health are necessary. While the total burden of HRI is not driven by EHEs, they present particularly pressing health risks that warrant public health preparedness. Many preparedness efforts will also protect against heat-health risks outside of EHEs. EHE preparedness is part of developing climate-resilient health systems and health care facilities and follows a familiar disaster risk reduction approach. HAPs are the most common, practical expression of strategies for protecting health against heat and include a number of common factors: centralized leadership, early warning, communication plans, strategies for reducing indoor and outdoor heat exposure, special focus on vulnerable groups, preparedness of health and social care systems, long-term planning to reduce risks, ongoing surveillance, and evaluation. Greater attention to evaluation, use of robust methods in evaluating HAP effectiveness, and study of implementation will enhance learning and refinement of programming to more effectively protect health against EHEs as the climate continues to change.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

AUTHOR CONTRIBUTIONS

J.J.H. conceived the analysis and outlined the manuscript. All authors participated in scoping literature reviews and drafted a portion of the manuscript. Specifically, J.J.H., Z.S.W., S.K.W., and T.B.I. drafted the section on Extreme Heat Events and Population Health. K.L.E. drafted the section on Climate Change and Extreme Heat Events. J.J.H., S.K.W., N.A.E., and Z.S.W. drafted the section on Climate-Resilient Health Systems. J.J.H., N.A.E., and G.M. drafted the section on Disaster Risk Reduction Applied to Extreme Heat Events. J.J.H. and N.A.E. drafted the section on Heat Action Plan Evaluation and Implementation. J.J.H. revised and edited the manuscript. All authors reviewed the final manuscript and provided final edits.

LITERATURE CITED

1. Abbinett J, Schramm PJ, Widerynski S, Saha S, Beavers S, et al. 2020. *Heat response plans: summary of evidence and strategies for collaboration and implementation*. Climate Health Tech. Rep., Clim. Health Program, Cent. Dis. Control Prev., Atlanta. **https://stacks.cdc.gov/view/cdc/93705**
2. AghaKouchak A, Chiang F, Huning LS, Love CA, Mallakpour I, et al. 2020. Climate extremes and compound hazards in a warming world. *Annu. Rev. Earth Planet. Sci.* 48:519–48
3. Anderson CA. 1989. Temperature and aggression: ubiquitous effects of heat on occurrence of human violence. *Psychol. Bull.* 106(1):74–96
4. Anderson GB, Dominici F, Wang Y, McCormack MC, Bell ML, Peng RD. 2013. Heat-related emergency hospitalizations for respiratory diseases in the Medicare population. *Am. J. Respir. Crit. Care Med.* 187:1098–103
5. Arias PA, Bellouin N, Coppola E, Jones RG, Krinner G, et al. 2021. Technical summary. See Ref. 85, pp. 33–144. **https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_TS.pdf**
6. Arnold L, Scheuerell MD, Busch Isaksen T. 2022. Mortality associated with extreme heat in Washington state: the historical and projected public health burden. *Atmosphere* 13(9):1392
7. ASPR (Assist. Secr. Prep. Response), TRACIE. 2022. *Climate change resilience and healthcare system considerations*. Rep., US Dep. Health Hum. Serv., Washington, DC. **https://files.asprtracie.hhs.gov/documents/aspr-tracie-climate-change-resilience-and-healthcare-system-considerations-508.pdf**
8. Barriopedro D, Fischer EM, Luterbacher J, Trigo RM, García-Herrera R. 2011. The hot summer of 2010: redrawing the temperature record map of Europe. *Science* 332(6026):220–24
9. B. C. Coroners Serv. 2022. *Extreme heat and human mortality: a review of heat-related deaths in B.C. in summer 2021*. Rep., Chief Coroner B. C., Burnaby. **https://www2.gov.bc.ca/assets/gov/birth-adoption-death-marriage-and-divorce/deaths/coroners-service/death-review-panel/extreme_heat_death_review_panel_report.pdf**
10. Bedi NS, Adams QH, Hess JJ, Wellenius GA. 2022. The role of cooling centers in protecting vulnerable individuals from extreme heat. *Epidemiology* 33(5):611–15
11. Bell ML, O'Neill MS, Ranjit N, Borja-Aburto VH, Cifuentes LA, Gouveia NC. 2008. Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. *Int. J. Epidemiol.* 37(4):796–804
12. Benmarhnia T, Bailey Z, Kaiser D, Auger N, King N, Kaufman JS. 2016. A difference-in-differences approach to assess the effect of a heat action plan on heat-related mortality, and differences in effectiveness according to sex, age, and socioeconomic status (Montreal, Quebec). *Environ. Health Perspect.* 124(11):1694–99

13. Benmarhnia T, Schwarz L, Nori-Sarma A, Bell ML. 2019. Quantifying the impact of changing the threshold of New York City heat emergency plan in reducing heat-related illnesses. *Environ. Res. Lett.* 14(11):114006
14. Bernard SM, McGeehin MA. 2004. Municipal heat wave response plans. *Am. J. Public Health* 94(9):1520–22
15. Bierens JJLM, Lunetta P, Tipton M, Warner DS. 2016. Physiology of drowning: a review. *Physiology* 31(2):147–66
16. Bouchama A, Knochel JP. 2002. Heat stroke. *N. Engl. J. Med.* 346:1978–88
17. Broadbent AM, Coutts AM, Tapper NJ, Demuzere M. 2018. The cooling effect of irrigation on urban microclimate during heatwave conditions. *Urban Clim*. 23:309–29
18. Burkart KG, Brauer M, Aravkin AY, Godwin WW, Hay SI, et al. 2021. Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the Global Burden of Disease Study. *Lancet* 398(10301):685–97
19. Burkom H, Loschen W, Wojcik R, Holtry R, Punjabi M, et al. 2021. Electronic Surveillance System for the Early Notification of Community-Based Epidemics (ESSENCE): overview, components, and public health applications. *JMIR Public Health Surveill*. 7(6):e26303
20. Calkins MM, Isaksen TB, Stubbs BA, Yost MG, Fenske RA. 2016. Impacts of extreme heat on emergency medical service calls in King County, Washington, 2007–2012: relative risk and time series analyses of basic and advanced life support. *Environ. Health.* 15(1):13
21. Calonge N, Brown L, Downey A, eds. 2020. *Evidence-based practices for public health emergency preparedness and response: assessment of and recommendations for the field*. Consens. Rep., Natl. Acad. Sci. Eng. Med., Washington, DC. **https://www.ncbi.nlm.nih.gov/books/NBK563990/pdf/Bookshelf_NBK563990.pdf**
22. Can G, Şahin Ü, Sayılı U, Dubé M, Kara B, et al. 2019. Excess mortality in Istanbul during extreme heat waves between 2013 and 2017. *Int. J. Environ. Res. Public Health*. 16(22):4348
23. Carbone EG, Thomas EV. 2018. Science as the basis of public health emergency preparedness and response practice: the slow but crucial evolution. *Am. J. Public Health.* 108(S5):S383–86
24. Carthey J, Chandra V. 2007. *The impact of climate change on healthcare facility infrastructure: a preliminary investigation of mitigation and adaptation strategies*. Presented at CHAA Conference—Future Health Facilities: Sustainability, Design, Financing and Research, Univ. N.S.W., Sydney, Feb. 19–20
25. Casanueva A, Burgstall A, Kotlarski S, Messeri A, Morabito M, et al. 2019. Overview of existing heat-health warning systems in Europe. *Int. J. Environ. Res. Public Health.* 16(15):2657
26. Chersich MF, Pham MD, Areal A, Haghighi MM, Manyuchi A, et al. 2020. Associations between high temperatures in pregnancy and risk of preterm birth, low birth weight, and stillbirths: systematic review and meta-analysis. *BMJ* 371:m3811
27. Conlon K, Austin C. 2019. A typology of interventions for public health adaptation to climate change. *Environ. Epidemiol.* 3:80
28. Copper FA, Mayigane LN, Pei Y, Charles D, Nguyen TN, et al. 2020. Simulation exercises and after action reviews—analysis of outputs during 2016–2019 to strengthen global health emergency preparedness and response. *Global. Health* 16(1):115
29. Coutts AM, Daly E, Beringer J, Tapper NJ. 2013. Assessing practical measures to reduce urban heat: green and cool roofs. *Build. Environ.* 70:266–76
30. Crandall CG, Wilson TE. 2015. Human cardiovascular responses to passive heat stress. *Compr. Physiol.* 5(1):17–43
31. Curriero FC, Heiner KS, Samet JM, Zeger SL, Strug L, Patz JA. 2002. Temperature and mortality in 11 cities of the eastern United States. *Am. J. Epidemiol.* 155(1):80–87
32. DeVine AC, Vu PT, Yost MG, Seto EYW. 2017. A geographical analysis of emergency medical service calls and extreme heat in King County, WA, USA (2007–2012). *Int. J. Environ. Res. Public Health* 14:937
33. Dixit SN, Bushara KO, Brooks BR. 1997. Epidemic heat stroke in a midwest community: risk factors, neurological complications and sequelae. *Wis. Med. J.* 96(5):39–41
34. Doubleday A, Errett NA, Ebi KL, Hess JJ. 2020. Indicators to guide and monitor climate change adaptation in the US Pacific Northwest. *Am. J. Public Health* 110:180–88

35. Dwyer IJ, Barry SJE, Megiddo I, White CJ. 2022. Evaluations of heat action plans for reducing the health impacts of extreme heat: methodological developments (2012–2021) and remaining challenges. *Int. J. Biometeorol.* 66(9):1915–27
36. Ebi K. 2011. Climate change and health risks: assessing and responding to them through "adaptive management." *Health Aff.* 30(5):924–30
37. Ebi KL. 2019. Effective heat action plans: research to interventions. *Environ. Res. Lett.* 14(12):122001
38. Ebi KL, Berry P, Hayes K, Boyer C, Sellers S, et al. 2018. Stress testing the capacity of health systems to manage climate change-related shocks and stresses. *Int. J. Environ. Res. Public Health.* 15(11):2370
39. Ebi KL, Boyer C, Ogden N, Paz S, Berry P, et al. 2021. Burning embers: synthesis of the health risks of climate change. *Environ. Res. Lett.* 16(4):044042
40. Ebi KL, Capon A, Berry P, Broderick C, de Dear R, et al. 2021. Hot weather and heat extremes: health risks. *Lancet* 398(10301):698–708
41. Ebi KL, Hess JJ. 2020. Health risks due to climate change: inequity in causes and consequences. *Health Aff.* 39(12):2056–62
42. Ebi KL, Ogden NH, Semenza JC, Woodward A. 2017. Detecting and attributing health burdens to climate change. *Environ. Health Perspect.* 125(8):085004
43. Epstein Y, Yanovich R. 2019. Heatstroke. *N. Engl. J. Med.* 380(25):2449–59
44. Errett NA, Dolan K, Hartwell C, Vickery J, Hess JJ. 2022. Adapting by their bootstraps: state and territorial public health agencies struggle to meet the mounting challenge of climate change. *Am. J. Public Health* 112:1379–81
45. FEMA (Fed. Emerg. Manag. Agency). 2010. *Developing and maintaining emergency operations plans: comprehensive preparedness guide (CPG) 101*. Rep., FEMA, Washington, DC. **https://www.fema.gov/sites/default/files/2020-05/CPG_101_V2_30NOV2010_FINAL_508.pdf**
46. FEMA (Fed. Emerg. Manag. Agency). 2022. Hazard mitigation planning. *Risk Management*. **https://www.fema.gov/emergency-managers/risk-management/hazard-mitigation-planning**
47. Filep EM, Murata Y, Endres BD, Kim G, Stearns RL, Casa DJ. 2020. Exertional heat stroke, modality cooling rate, and survival outcomes: a systematic review. *Medicina* 56(11):589
48. Gasparrini A, Guo Y, Hashizume M, Lavigne E, Zanobetti A, et al. 2015. Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *Lancet* 386(9991):369–75
49. Gauer R, Meyers BK. 2019. Heat-related illnesses. *Am. Fam. Phys.* 99(8):482–89
50. Gifford RM, Todisco T, Stacey M, Fujisawa T, Allerhand M, et al. 2019. Risk of heat illness in men and women: a systematic review and meta-analysis. *Environ. Res.* 171:24–35
51. Gonick SA, Errett NA. 2018. Integrating climate change into hazard mitigation planning: a survey of state hazard mitigation officers. *Sustainability* 10(11):4150
52. Gronlund CJ, Zanobetti A, Schwartz JD, Wellenius GA, O'Neill MS. 2014. Heat, heat waves, and hospital admissions among the elderly in the United States, 1992–2006. *Environ. Health Perspect.* 122(11):1187–92
53. Guardaro M, Messerschmidt M, Hondula DM, Grimm NB, Redman CL. 2020. Building community heat action plans story by story: a three neighborhood case study. *Cities* 107:102886
54. Haghighi MM, Wright CY, Ayer J, Urban MF, Pham MD, et al. 2021. Impacts of high environmental temperatures on congenital anomalies: a systematic review. *Int. J. Environ. Res. Public Health* 18(9):4910
55. Hasan F, Marsia S, Patel K, Agrawal P, Razzak JA. 2021. Effective community-based interventions for the prevention and management of heat-related illnesses: a scoping review. *Int. J. Environ. Res. Public Health* 18(16):8362
56. Hess JJ, Sathish LM, Knowlton K, Saha S, Dutta P, et al. 2018. Building resilience to climate change: pilot evaluation of the impact of India's first heat action plan on all-cause mortality. *J. Environ. Public Health* 2018:7973519
57. Hess JJ, McDowell JZ, Luber G. 2012. Integrating climate change adaptation into public health practice: using adaptive management to increase adaptive capacity and build resilience. *Environ. Health Perspect.* 120(2):171–79
58. Honda Y, Kondo M, McGregor G, Kim H, Guo Y-L, et al. 2014. Heat-related mortality risk model for climate change impact projection. *Environ. Health Prev. Med.* 19(1):56–63

59. Inst. Med. Natl. Acad., Comm. Post-Disaster Recovery Community's Public Health Med. Soc. Serv. 2015. *Healthy, resilient, and sustainable communities after disasters: strategies, opportunities, and planning for recovery*. Rep., Natl. Acad. Press, Washington, DC
60. Isaksen TB, Fenske RA, Hom EK, Ren Y, Lyons H, Yost MG. 2016. Increased mortality associated with extreme-heat exposure in King County, Washington, 1980–2010. *Int. J. Biometeorol.* 60(1):85–98
61. Isaksen TB, Yost MG, Hom EK, Ren Y, Lyons H, Fenske RA. 2015. Increased hospital admissions associated with extreme-heat exposure in King County, Washington, 1990–2010. *Rev. Environ. Health* 30:51–64
62. Iverson SA, Gettel A, Bezold CP, Goodin K, McKinney B, et al. 2020. Heat-associated mortality in a hot climate: Maricopa County, Arizona, 2006–2016. *Public Health Rep*. 135(5):631–39
63. Jacobs SJ, Gallant AJE, Tapper NJ, Li D. 2018. Use of cool roofs and vegetation to mitigate urban heat and improve human thermal stress in Melbourne, Australia. *J. Appl. Meteorol. Climatol.* 57(8):1747–64
64. Jay O, Capon A, Berry P, Broderick C, de Dear R, et al. 2021. Reducing the health effects of hot weather and heat extremes: from personal cooling strategies to green cities. *Lancet* 398(10301):709–24
65. Kabisch N, Korn H, Stadler J, Bonn A. 2017. Nature-based solutions to climate change adaptation in urban areas—linkages between science, policy and practice. In *Nature-Based Solutions to Climate Change Adaptation in Urban Areas. Theory and Practice of Urban Sustainability Transitions*, ed. N Kabisch, H Korn, J Stadler, A Bonn, pp. 1–11. Cham, Switz.: Springer
66. Keith L, Meerow S, Wagner T. 2019. Planning for extreme heat: a review. *J. Extrem. Events* 6(3–4):2050003
67. Kennedy M, Gonick SA, Errett NA. 2021. Are we ready to build back "healthier?": an exploratory analysis of US state-level disaster recovery plans. *Int. J. Environ. Res. Public Health* 18:8003
68. Kenny GP, Yardley J, Brown C, Sigal RJ, Jay O. 2010. Heat stress in older individuals and patients with common chronic diseases. *CMAJ* 182(10):1053–60
69. Khan Y, Fazli G, Henry B, de Villa E, Tsamis C, et al. 2015. The evidence base of primary research in public health emergency preparedness: a scoping review and stakeholder consultation. *BMC Public Health* 15:432
70. Kim J, Lee A, Rossin-Slater M. 2021. What to expect when it gets hotter: the impacts of prenatal exposure to extreme temperature on maternal health. *Am J. Health Econ.* 7:281–305
71. Kim K, Jung J, Schollaert C, Spector JT. 2021. A comparative assessment of cooling center preparedness across twenty-five U.S. cities. *Int. J. Environ. Res. Public Health* 18(9):4801
72. Knowlton K, Kulkarni SP, Azhar GS, Mavalankar D, Jaiswal A, et al. 2014. Development and implementation of South Asia's first heat-health action plan in Ahmedabad (Gujarat, India). *Int. J. Environ. Res. Public Health* 11(4):3473–92
73. Knowlton K, Rotkin-Ellman M, King G, Margolis HG, Smith D, et al. 2009. The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environ. Health Perspect.* 117(1):61–67
74. Koch M, Matzke I, Huhn S, Gunga H-C, Maggioni MA, et al. 2022. Wearables for measuring health effects of climate change-induced weather extremes: scoping review. *JMIR mHealth uHealth* 10(9):e39532
75. Kotharkar R, Ghosh A. 2022. Progress in extreme heat management and warning systems: a systematic review of heat-health action plans (1995–2020). *Sustain. Cities Soc.* 76:103487
76. Kovats RS, Hajat S. 2008. Heat stress and public health: a critical review. *Annu. Rev. Public Health* 29:41–55
77. Layton JB, Li W, Yuan J, Gilman JP, Horton DB, Setoguchi S. 2020. Heatwaves, medications, and heat-related hospitalization in older Medicare beneficiaries with chronic conditions. *PLOS ONE* 15(12):e0243665
78. Lipman GS, Eifling KP, Ellis MA, Gaudio FG, Otten EM, et al. 2014. Wilderness Medical Society practice guidelines for the prevention and treatment of heat-related illness: 2014 update. *Wilderness Environ. Med.* 25(4 Suppl.):S55–65
79. Luber G, McGeehin M. 2008. Climate change and extreme heat events. *Am. J. Prev. Med.* 35(5):429–35

80. Madrigano J, Lane K, Petrovic N, Ahmed M, Blum M, Matte T. 2018. Awareness, risk perception, and protective behaviors for extreme heat and climate change in New York City. *Int. J. Environ. Res. Public Health* 15(7):1433
81. Marinucci GD, Luber G, Uejio CK, Saha S, Hess JJ. 2014. Building resilience against climate effects—a novel framework to facilitate climate readiness in public health agencies. *Int. J. Environ. Res. Public Health*. 11(6):6433–58
82. Marsteller JA, Wen M, Hsu Y-J, Bauer LC, Schwann NM, et al. 2015. Safety culture in cardiac surgical teams: data from five programs and national surgical comparison. *Ann. Thorac. Surg.* 100(6):2182–89
83. Martinez GS, Kendrovski V, Salazar MA, de'Donato F, Boeckmann M. 2022. Heat-health action planning in the WHO European Region: status and policy implications. *Environ. Res.* 214(Pt. 1):113709
84. Martinez GS, Linares C, Ayuso A, Kendrovski V, Boeckmann M, Diaz J. 2019. Heat-health action plans in Europe: challenges ahead and how to tackle them. *Environ. Res.* 176:108548
85. Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C. 2021. *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Rep., Cambridge Univ., Cambridge, UK. **https://report.ipcc.ch/ar6/wg1/IPCC_AR6_WGI_FullReport.pdf**
86. Matthews JBR, ed. 2018. Annex I: glossary. In *Global Warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*, ed. V Masson-Delmotte, P Zhai, H-O Pörtner, D Roberts, J Skea, et al., pp. 3–24. Cambridge, UK: Cambridge Univ. Press
87. McGregor GR, Bessemoulin P, Ebi K, Menne B, eds. 2015. *Heatwaves and health: guidance on warning-system development*. WMO 1142, World Meteorol. Organ., World Health Organ., Geneva. **https://library.wmo.int/doc_num.php?explnum_id=3371**
88. McGregor GR, Vanos JK. 2018. Heat: a primer for public health researchers. *Public Health* 161:138–46
89. Meerow S, Keith L. 2022. Planning for extreme heat. *J. Am. Plan. Assoc.* 88(3):319–34
90. Michelozzi P, de'Donato FK, Bargagli AM, D'Ippoliti D, De Sario M, et al. 2010. Surveillance of summer mortality and preparedness to reduce the health impact of heat waves in Italy. *Int. J. Environ. Res. Public Health* 7(5):2256–73
91. Nairn J, Fawcett R. 2013. *Defining heatwaves: heatwave defined as a heat-impact event servicing all community and business sectors in Australia*. Tech. Rep. 60, Cent. Aust. Weather Clim. Res., Melbourne. **https://www.cawcr.gov.au/technical-reports/CTR_060.pdf**
92. Nairn J, Ostendorf B, Bi P. 2018. Performance of excess heat factor severity as a global heatwave health impact index. *Int. J. Environ. Res. Public Health* 15(11):2494
93. Ndriko Mayigane L, Isla N, Bruni E, Copper F, Chungong S. 2019. *The global practice of after action review: a systematic review of the literature*. WHO/WHE/CPI/2019.9, World Health Organ., Geneva
94. NOAA (Natl. Ocean. Atmos. Adm.). 2022. During a heat wave. *National Weather Service*. **https://www.weather.gov/safety/heat-during**
95. Nori-Sarma A, Sun S, Sun Y, Spangler KR, Oblath R, et al. 2022. Association between ambient heat and risk of emergency department visits for mental health among US adults, 2010 to 2019. *JAMA Psychiatry* 79(4):341–49
96. O'Meara P, Stirling C, Ruest M, Martin A. 2016. Community paramedicine model of care: an observational, ethnographic case study. *BMC Health Serv. Res.* 16:39
97. O'Neill MS, Carter R, Kish JK, Gronlund CJ, White-Newsome JL, et al. 2009. Preventing heat-related morbidity and mortality: new approaches in a changing climate. *Maturitas* 64(2):98–103
98. O'Neill MS, Zanobetti A, Schwartz J. 2003. Modifiers of the temperature and mortality association in seven US cities. *Am. J. Epidemiol.* 157(12):1074–82
99. Pace NP, Vassallo J, Calleja-Agius J. 2021. Gestational diabetes, environmental temperature and climate factors—from epidemiological evidence to physiological mechanisms. *Early Hum. Dev.* 155:105219

100. Pan C-L, Chiu C-W, Wen J-C. 2014. Adaptation and promotion of emergency medical service transportation for climate change. *Medicine* 93(27):e186
101. Patel L, Conlon KC, Sorensen C, McEachin S, Nadeau K, et al. Climate change and extreme heat events: how health systems should prepare. *NEJM Catalyst* 3(7). **https://doi.org/10.1056/CAT.21.0454**
102. Paterson J, Berry P, Ebi K, Varangu L. 2014. Health care facilities resilient to climate change impacts. *Int. J. Environ. Res. Public Health* 11(12):13097–116
103. Pendergrast CB, Errett NA. 2021. Public health requirements and authorities in state statutory disaster recovery law: a cross-sectional legal assessment. *Health Secur*. 19(3):271–79
104. Philip SY, Kew SF, van Oldenborgh GJ, Anslow FS, Seneviratne SI, et al. 2021. Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada in June 2021. *Earth Syst. Dynam. Discuss.* **https://doi.org/10.5194/esd-2021-90**
105. Public Health Engl., Natl. Health Serv. 2015. *Heatwave plan for England: protecting health and reducing harm from severe heat and heatwaves*. Rep. GOV-12960, Public Health Engl., London. **https://climate-adapt.eea.europa.eu/en/metadata/case-studies/heatwave-plan-for-england/document-1_heatwave-plan-2015.pdf**
106. Ragettli MS, Röösli M. 2019. [Heat-health action plans to prevent heat-related deaths-experiences from Switzerland]. *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz* 62(5):605–11
107. Ravanelli N, Casasola W, English T, Edwards KM, Jay O. 2019. Heat stress and fetal risk. Environmental limits for exercise and passive heat stress during pregnancy: a systematic review with best evidence synthesis. *Br. J. Sports Med.* 53(13):799–805
108. Riley K, Wilhalme H, Delp L, Eisenman DP. 2018. Mortality and morbidity during extreme heat events and prevalence of outdoor work: an analysis of community-level data from Los Angeles County, California. *Int. J. Environ. Res. Public Health* 15(4):580
109. Robine J-M, Cheung SLK, Le Roy S, Van Oyen H, Griffiths C, et al. 2008. Death toll exceeded 70,000 in Europe during the summer of 2003. *C. R. Biol.* 331(2):171–78
110. Romanello M, McGushin A, Di Napoli C, Drummond P, Hughes N, et al. 2021. The 2021 report of the *Lancet* Countdown on health and climate change: code red for a healthy future. *Lancet* 398(10311):1619–62
111. Roos N, Kovats S, Hajat S, Filippi V, Chersich M, et al. 2021. Maternal and newborn health risks of climate change: a call for awareness and global action. *Acta Obstet. Gynecol. Scand.* 100(4):566–70
112. Rublee C, Dresser C, Giudice C, Lemery J, Sorensen C. 2021. Evidence-based heatstroke management in the emergency department. *West. J. Emerg. Med.* 22(2):186–95
113. Rylander C, Øyvind Odland J, Manning Sandanger T. 2013. Climate change and the potential effects on maternal and pregnancy outcomes: an assessment of the most vulnerable—the mother, fetus, and newborn child. *Glob. Health Action* 6(1):19538
114. Salas RN, Friend TH, Bernstein A, Jha AK. 2020. Adding a climate lens to health policy in the United States. *Health Aff.* 39(12):2063–70
115. Samuels L, Nakstad B, Roos N, Bonell A, Chersich M, et al. 2022. Physiological mechanisms of the impact of heat during pregnancy and the clinical implications: review of the evidence from an expert group meeting. *Int. J. Biometeorol.* 66(8):1505–13
116. Santamouris M, Ding L, Fiorito F, Oldfield P, Osmond P, et al. 2017. Passive and active cooling for the outdoor built environment—analysis and assessment of the cooling potential of mitigation technologies using performance data from 220 large scale projects. *Solar Energy* 154:14–33
117. Sanz-Barbero B, Linares C, Vives-Cases C, González JL, López-Ossorio JJ, Díaz J. 2018. Heat wave and the risk of intimate partner violence. *Sci. Total Environ.* 644:413–19
118. Schramm PJ, Vaidyanathan A, Radhakrishnan L, Gates A, Hartnett K, Breysse P. 2021. Heat-related emergency department visits during the northwestern heat wave—United States, June 2021. *MMWR* 70(29):1020–21
119. Schwartz J. 2005. Who is sensitive to extremes of temperature? A case-only analysis. *Epidemiology* 16(1):67–72
120. Schwartz J, Samet JM, Patz JA. 2004. Hospital admissions for heart disease: the effects of temperature and humidity. *Epidemiology* 15(6):755–61

121. Shao Y, Xu J, Qiao Y, Shao Y, Fei J-M. 2020. The effects of temperature on dynamics of psychiatric outpatients. *Front. Psychiatry* 11:523059
122. Sheffield PE, Landrigan PJ. 2011. Global climate change and children's health: threats and strategies for prevention. *Environ. Health Perspect.* 119(3):291–98
123. Sheridan SC. 2007. A survey of public perception and response to heat warnings across four North American cities: an evaluation of municipal effectiveness. *Int. J. Biometeorol.* 52(1):3–15
124. Son J-Y, Lee J-T, Anderson GB, Bell ML. 2012. The impact of heat waves on mortality in seven major cities in Korea. *Environ. Health Perspect.* 120(4):566–71
125. Sorensen C, Hess J. 2022. Treatment and prevention of heat-related illness. *N. Engl. J. Med.* 387:1404–13
126. Spector JT, Bonauto DK, Sheppard L, Busch-Isaksen T, Calkins M, et al. 2016. A case-crossover study of heat exposure and injury risk in outdoor agricultural workers. *PLOS ONE* 11(10):e0164498
127. Stone B Jr., Mallen E, Rajput M, Gronlund CJ, Broadbent AM, et al. 2021. Compound climate and infrastructure events: how electrical grid failure alters heat wave risk. *Environ. Sci. Technol.* 55(10):6957–64
128. Tiihonen J, Halonen P, Tiihonen L, Kautiainen H, Storvik M, Callaway J. 2017. The association of ambient temperature and violent crime. *Sci. Rep.* 7(1):6543
129. Toloo G, FitzGerald G, Aitken P, Verrall K, Tong S. 2013. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. *Int. J. Public Health* 58(5):667–81
130. Toloo GS, Fitzgerald G, Aitken P, Verrall K, Tong S. 2013. Are heat warning systems effective? *Environ. Health* 12:27
131. Tuckson RV, Dzau VJ, Lurie N. 2017. Creating healthy communities after disasters. *N. Engl. J. Med.* 377(19):1806–8
132. UNDRR (UN Off. Disaster Risk Reduct.). 2020. Disaster risk management. *Terminology*. **https://www.undrr.org/terminology/disaster-risk-management**
133. UNDRR (UN Off. Disaster Risk Reduct.). 2022. Disaster risk. *PreventionWeb*. **https://www.preventionweb.net/understanding-disaster-risk/component-risk/disaster-risk#:~:text=Disaster%20risk%20is%20widely%20recognized,and%20places%20vulnerable%20and%20exposed**
134. Vicedo-Cabrera AM, Scovronick N, Sera F, Royé D, Schneider R, et al. 2021. The burden of heat-related mortality attributable to recent human-induced climate change. *Nat. Clim. Chang.* 11(6):492–500
135. Wallace RF, Kriebel D, Punnett L, Wegman DH, Amoroso PJ. 2007. Prior heat illness hospitalization and risk of early death. *Environ. Res.* 104(2):290–95
136. Wang P, Goggins WB, Shi Y, Zhang X, Ren C, Ka-Lun Lau K. 2021. Long-term association between urban air ventilation and mortality in Hong Kong. *Environ. Res.* 197:111000
137. Weinberger KR, Harris D, Spangler KR, Zanobetti A, Wellenius GA. 2020. Estimating the number of excess deaths attributable to heat in 297 United States counties. *Environ. Epidemiol.* 4(3):e096
138. Weinberger KR, Zanobetti A, Schwartz J, Wellenius GA. 2018. Effectiveness of National Weather Service heat alerts in preventing mortality in 20 US cities. *Environ. Int.* 116:30–38
139. White-Newsome JL, Ekwurzel B, Baer-Schultz M, Ebi KL, O'Neill MS, Anderson GB. 2014. Survey of county-level heat preparedness and response to the 2011 summer heat in 30 U.S. States. *Environ. Health Perspect.* 122(6):573–79
140. White-Newsome JL, McCormick S, Sampson N, Buxton MA, O'Neill MS, et al. 2014. Strategies to reduce the harmful effects of extreme heat events: a four-city study. *Int. J. Environ. Res. Public Health* 11(2):1960–88
141. Whiteoak K, Saigar J. 2019. *Estimating the economic benefits of urban heat island mitigation—economic analysis*. Final Rep., Coop. Res. Cent. Water Sensitive Cities, Melbourne, Aust. **https://watersensitivecities.org.au/wp-content/uploads/2019/08/UHI-mitigation-economic-benefits-Final-Report_approve.pdf**
142. Whitman S, Good G, Donoghue ER, Benbow N, Shou W, Mou S. 1997. Mortality in Chicago attributed to the July 1995 heat wave. *Am. J. Public Health* 87(9):1515–18
143. WHO (World Health Organ.). 2015. *Operational framework for building climate resilient health systems*. Rep., WHO, Geneva. **https://www.who.int/publications/i/item/9789241565073**

144. WHO (World Health Organ.). 2020. *WHO guidance for climate-resilient and environmentally sustainable health care facilities*. Rep., WHO, Geneva. **https://www.who.int/publications/i/item/9789240012226**
145. WMO (World Meteorol. Organ.). 2022. Heat wave. *UNTERM*. **https://unterm.un.org/unterm2/en/view/506bdf0a-a748-4c8d-b806-19143c9d5a7f**
146. World Weather Attrib. 2022. *Without human-caused climate change temperatures of 40°C in the UK would have been extremely unlikely*. Rep., World Weather Attrib. **https://www.worldweatherattribution.org/without-human-caused-climate-change-temperatures-of-40c-in-the-uk-would-have-been-extremely-unlikely/**
147. Xu Z, Sheffield PE, Su H, Wang X, Bi Y, Tong S. 2014. The impact of heat waves on children's health: a systematic review. *Int. J. Biometeorol.* 58(2):239–47
148. Yang J, Yin P, Sun J, Wang B, Zhou M, et al. 2019. Heatwave and mortality in 31 major Chinese cities: definition, vulnerability and implications. *Sci. Total Environ.* 649:695–702
149. Zachariah M, Arulalan T, AchutaRao K, Saeed F, Jha R, et al. 2022. *Climate change made devastating early heat in India and Pakistan 30 times more likely*. Rep., World Weather Attrib. **https://www.worldweatherattribution.org/wp-content/uploads/India_Pak-Heatwave-scientific-report.pdf**
150. Zhang M, Mitchell D, Thompson V. 2021. Violence and mental health are likely get worse in a warming world. *Conversation*, Oct. 27. **https://theconversation.com/violence-and-mental-health-are-likely-to-get-worse-in-a-warming-world-169547**
151. Zhang Y, Yu C, Wang L. 2017. Temperature exposure during pregnancy and birth outcomes: an updated systematic review of epidemiological evidence. *Environ. Pollut.* 225:700–12

Annual Review of
Public Health

Volume 44, 2023

Contents

Epidemiology and Biostatistics

Social Environment and Behavior

Environmental and Occupational Health

Public Health Practice and Policy

Health Services

Indexes

Errata

An online log of corrections to *Annual Review of Public Health* articles may be found at http://www.annualreviews.org/errata/publhealth

Related Articles

From the ***Annual Review of Animal Biosciences***, Volume 11 (2023)

From the ***Annual Review of Biomedical Data Science***, Volume 5 (2022)

From the ***Annual Review of Cancer Biology***, Volume 6 (2022)

From the ***Annual Review of Clinical Psychology***, Volume 18 (2022)

From the ***Annual Review of Criminology***, Volume 6 (2023)

The Opioid Crisis: The War on Drugs Is Over. Long Live the War on Drugs
Marie Gottschalk

From the ***Annual Review of Developmental Psychology***, Volume 4 (2022)

Practice and Policy Regarding Child Neglect: Lessons from Studies of Institutional Deprivation
Charles H. Zeanah and Lucy S. King

From the ***Annual Review of Economics***, Volume 14 (2022)

The Impact of Health Information and Communication Technology on Clinical Quality, Productivity, and Workers
Ari Bronsoler, Joseph Doyle, and John Van Reenen

The Economics of the COVID-19 Pandemic in Poor Countries
Edward Miguel and Ahmed Mushfiq Mobarak

The Affordable Care Act After a Decade: Industrial Organization of the Insurance Exchanges
Benjamin Handel and Jonathan Kolstad

From the ***Annual Review of Environment and Resources***, Volume 47 (2022)

COVID-19 and the Environment: Short-Run and Potential Long-Run Impacts
Noah S. Diffenbaugh

Sustainability in Health Care
Howard Hu, Gary Cohen, Bhavna Sharma, Hao Yin, and Rob McConnell

Agrochemicals, Environment, and Human Health
P. Indira Devi, M. Manjula, and R.V. Bhavani

The Concept of Adaptation
Ben Orlove

From the ***Annual Review of Law and Social Science***, Volume 18 (2022)

Good Law to Fight Bad Bugs: Legal Responses to Epidemics
Carol A. Heimer and Clay Davis

Environmental Legal Mobilization
Lisa Vanhala

From the ***Annual Review of Medicine***, Volume 74 (2023)

COVID-19: Challenges of Viral Variants
Jana L. Jacobs, Ghady Haidar, and John W. Mellors

Post-COVID-19 Condition
Ani Nalbandian, Amar D. Desai, and Elaine Y. Wan

From the ***Annual Review of Nutrition***, Volume 42 (2022)

From the ***Annual Review of Political Science***, Volume 25 (2022)

From the ***Annual Review of Psychology***, Volume 74 (2023)

From the ***Annual Review of Statistics and Its Application***, Volume 9 (2022)

From the ***Annual Review of Virology***, Volume 9 (2022)