Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

One Earth

CellPress
OPEN ACCESS

Review

Impacts of warming on outdoor worker well-being in the tropics and adaptation options

Yuta J. Masuda,[1,15,*] **Luke A. Parsons,**[2,3,15] **June T. Spector,**[4] **David S. Battisti,**[5] **Brianna Castro,**[6] **James T. Erbaugh,**[3,7] **Edward T. Game,**[8] **Teevrat Garg,**[9] **Peter Kalmus,**[10] **Timm Kroeger,**[3] **Vimal Mishra,**[11] **Drew Shindell,**[2] **Michelle Tigchelaar,**[12,14] **Nicholas H. Wolff,**[3] **and Lucas R. Vargas Zeppetello**[13]
[1]Paul G. Allen Family Foundation, Seattle, WA, USA
[2]Nicholas School of the Environmental, Duke University, Durham, NC, USA
[3]Global Science, The Nature Conservancy, Arlington, VA, USA
[4]Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, WA, USA
[5]Department of Atmospheric Sciences, University of Washington, Seattle, WA, USA
[6]Department of Sociology, Harvard University, Cambridge, MA, USA
[7]Department of Environmental Studies, Dartmouth College, Hanover, NH, USA
[8]Asia Pacific Program, The Nature Conservancy, Brisbane, QLD, Australia
[9]School of Global Policy and Strategy, University of California, San Diego, La Jolla, CA, USA
[10]NASA Jet Propulsion Laboratory, Pasadena, CA, USA
[11]Indian Institute of Technology Gandhinagar, Gandhinagar, India
[12]World Fish, Bayan Lepas, Penang, Malaysia
[13]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA
[14]Center for Ocean Solutions, Stanford University, Stanford, CA, USA
[15]These authors contributed equally
*Correspondence: yutam@pgafamilyfoundation.org
https://doi.org/10.1016/j.oneear.2024.02.001

SUMMARY

Over a billion outdoor workers live in the tropics, where nearly a fifth of all hours in the year are hot and humid enough to exceed recommended safety thresholds for workers conducting heavy labor. Reviews have focused on heat impacts on worker health, well-being, and productivity, but synthesis on how to increase resilience to heat for outdoor workers is lacking. Here we assess current and future heat exposure in the tropics and review four bodies of literature on heat impacts on workers. We also synthesize knowledge about mitigation and adaptation uncertainties as well as the actions that can be taken to strengthen worker resilience. We show that under an additional 1°C of warming, ~800 million people in the tropics will live in areas where heavy work should be limited for over half of the hours in the year. Our review provides primary, secondary, and tertiary solutions that will inform policies and practices as well as research that is needed to bolster worker resilience and well-being.

INTRODUCTION

The harmful effects of global warming are already present for many people in the tropics, where high temperatures and humidity are often a feature of everyday life, especially for outdoor workers.[1–3] The human and economic costs are significant. The cost of lost potential labor productivity for outdoor workers from heat is already estimated at several hundred billion to over 2 trillion dollars per year (in 2017 purchasing power parity adjusted dollars).[2] Reports on the health, adaptation strategies, and well-being of outdoor workers to date indicate that impacts are pervasive across the tropics.[1,4] Given the world is projected to warm approximately 3.0°C above pre-industrial levels by the end of the century (5%–95%: 2.1°C–4.3°C),[5] a future with more extreme heat and more pronounced adverse impacts for outdoor workers in the tropics is likely unless widespread adaptation measures are implemented. Perversely, these populations are often the least resilient to climate-change impacts and have contributed the least to greenhouse gas emissions.[6] For the purposes of our review, we define the tropics as the geographic region between 30° latitude north and south of the equator. Although this geography includes diverse regions, including dry deserts, coastal regions dotted with mangroves, and tropical forests, it is a region generally characterized by relatively small seasonal temperature variations and high humidity. Importantly, the tropics are home to most of the world's poor, many of whom work in climate-exposed occupations.[7] Several countries in the tropics also have some of the highest population growth rates in the world,[8] increasing the future number of outdoor workers that will be at risk.

A significant proportion of outdoor workers in the tropics faces substantial exposure and is less resilient to environmental stressors. In many low-latitude countries, around half of the working-age population is engaged in outdoor occupations, specifically in construction, agriculture, fisheries, and forestry sectors.[9] These estimates likely undercount the true population working in hot environments because they do not account for those engaged in manufacturing and informal household work,

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

such as firewood and water collection, and because of the lack of comprehensive, representative, and harmonized data on workers. Nearly 60%–70% of the global labor force participates in the informal economy,[7,10] with approximately 67% and 90% of workers older than 15 years in informal employment in emerging and developing countries, respectively.[11] A disproportionate number of workers in the tropics participate in informal industries (e.g., informal extractive operations) that lack entitlements and formal protections. In addition to elevated heat exposure, risk for outdoor workers in tropical countries is compounded by limited adaptive capacity, stemming from factors such as inadequate infrastructure development (such as electricity and clean piped water) as well as the absence of robust labor regulations commonly observed in high-income countries.[12] These dangers are likely even more pronounced for those working in informal sectors.[13] For brevity, here and throughout our paper when we mention "workers" we are referring to those workers in exposed outdoor industries.

Several reviews have highlighted how warming has impacted, and will impact, labor productivity[14,15] and the health and well-being of workers in the tropics.[1,16–23] These reviews synthesized impacts on workers (e.g., productivity, heat strain, labor supply), establishing that both the scale and magnitude of impacts are significant and growing. By some estimates the global number of impacted workers is larger than the total population of Mexico (e.g., global estimates based on 1.5°C warming suggest that by 2030 annual productivity losses will be equivalent to 80–136 million full-time jobs[1,7]), with the estimated annual global economic impact being equivalent to the gross domestic product (GDP) of Hungary.[2] The largest per-capita heavy-labor productivity losses are found near the equator, regardless of the choice of humid heat metric or assumptions about worker responses to humid heat exposure.[2,24] Yet we are unaware of efforts to synthesize whether and how workers in the tropics can bolster resilience in the face of further warming, either on their own or through changes in policies that regulate land use, labor rights, emissions, or other policies relevant to heat exposure.

Here we synthesize evidence across four bodies of literature that align with our framework and are rarely fully integrated, including examples of (1) public health literature assessing how hot environments impact heat stress and illness,[1] (2) physical science literature summarizing drivers of increasing ambient heat in the tropics,[4,25–27] (3) heat impacts literature focused on estimating large-scale humid heat impacts on workers,[2,28,29] and (4) social science literature documenting the range of adaptations at various levels.[30–32] Pulling from these diverse bodies of evidence, the objective of our review is to synthesize what is known about (1) the source, scale, and magnitude of deleterious heat impacts and (2) how workers and relevant institutions are adapting to increasing heat, thus advancing broader knowledge about future directions for research and practice for mitigating and adapting to heat. We find that nearly one-fifth of all hours in the year already exceed safety thresholds for the average outdoor worker conducting heavy labor in the tropics, and that under an additional 1°C of global warming nearly one-third of all hours in the year exceed safety thresholds for heavy labor. We also find that worker adaptations remain understudied, but at the same time there are clear actions that can be taken by governments, communities, households, and individual workers to increase their resilience to heat. More work is needed to understand maladaptation, how multiple environmental stressors impact workers in the tropics, and how all stakeholders can provide access to existing and new solutions to address adverse humid heat impacts.

Approach

Our review highlights the impacts of warming on worker well-being in the tropics and focuses on modifiable factors that would increase resilience for these workers (B and C in Figure 1).[33] Modifiable factors include: physical modifications that directly reduce ambient heat exposure (e.g., air-conditioning); administrative factors that reduce metabolic heat generation or ambient heat exposure (e.g., rest breaks, reductions in work pace, shifting work to cooler parts of the day); clothing that allows for heat dissipation; structural factors (e.g., reducing disincentives to take breaks or reduce work pace)[34]; community- or household-level adaptations; land-use planning; and built environments that facilitate lower heat exposure.[35] We consider a wide range of actions and include a diverse set of actors (individuals, employers, households, and communities, as well as governments) and timescales. We refine how modifiable factors are conceptualized in the public health literature[36–38] by clarifying that these factors should be adjustable on a timescale relevant to the specific needs of the actors involved. For example, an individual may not be able to modify their chronic health conditions on a short timescale but could modify heat adaptation behaviors, particularly with complementary supportive actions at higher levels (e.g., by employers or the government). We include emissions reduction (e.g., rapid reductions in fossil fuel emissions) as a modifiable factor in our review because this action is feasible through government action. We aim to identify and highlight modifiable factors because they represent areas in which further research and policy can reduce vulnerability and bolster worker resilience.

Our organizing framework is presented in Figure 1. It builds on the Spector et al.[35] framework, which links the hierarchy of controls and social-ecological frameworks and aligns with other frameworks on vulnerability and resilience.[39,40] Our framework articulates action types ranging from adaptation to mitigation for moderating adverse heat impacts. The framework outlines a systematic process for identifying who could realistically implement each modifying factor and on what timescale and identifies the limitations each actor may face in adopting such modifications. To increase resilience, it is important to consider the full range of modifying factors and how they align. For workers in low- and middle-income countries, many possible actions (i.e., policies, regulations and plans, engineering, administrative controls and training, personal protective equipment) are less likely to be implemented.[41] Our framework allows for a broad assessment of the limitations and challenges for facilitating reasonable adaptations to heat stress and can also be used to explore potential tradeoffs that may influence resilience at various temporal and spatial scales. For example, labor regulations could increase safety protections across entire sectors in the formal economy, but in emerging economies these regulations may lead to non-trivial feasibility concerns for informal sector employers and workers. The framework focuses our review on potential solutions. We do so by first reviewing the

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

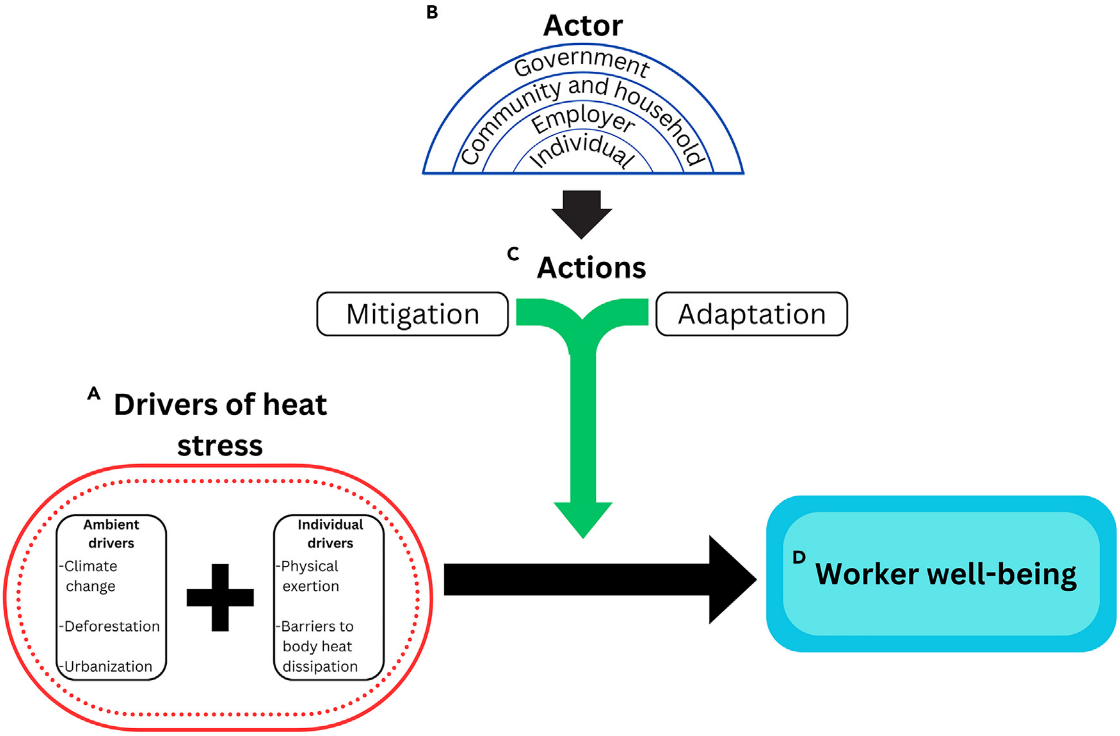

Figure 1. Heat impacts and modifiable factors for workers in the tropics
Three components affect worker well-being (D). Drivers of heat stress and sensitivity factors are shown in (A). Ambient drivers of heat stress include climate change, deforestation, and urbanization, while individual drivers include factors such as physical exertion and barriers to internal body heat dissipation, which are in turn influenced by individual factors such as socioeconomic status (e.g., may influence workload) and health conditions. Four nested levels of actors are outlined in (B), and (C) represents the range of actions actors can take to moderate heat impacts. These include actions that mitigate ambient drivers of heat, such as land-use planning to prevent deforestation, reducing emissions, or restructuring labor, as well as adaptive actions that can moderate heat exposure and sensitivity such as adjusting clothing, shifting work times, and acclimatization.

four bodies of literature discussed above and then present primary, secondary, and tertiary solutions that can be enacted by various actors. We close by highlighting critical research gaps to advance science and practice for increasing worker resilience in the tropics.

HEAT-EXPOSURE IMPACTS ON HUMAN HEALTH AND PRODUCTIVITY

Heat has both near-term (i.e., acute) and longer-term (i.e., chronic) effects on human health (Figure 2). The human body responds to heat by redistributing blood flow to the skin, where heat is transferred to the environment through dilation of blood vessels, or vasodilation, and through sweating and evaporative heat loss.[42] This thermoregulatory response increases cardiac oxygen demand, which can outstrip supply among those with underlying cardiac disease and ultimately lead to cardiac ischemia, infarction, and collapse. Dehydration decreases blood volume and can compound these effects. Dehydration can also increase the risk of acute kidney injury. When the thermoregulatory capacity of the body is exceeded, the body temperature can no longer be maintained in a normal narrow range, and body temperature rises and heat stroke can develop.[43] Although classical heat stroke occurs primarily in the elderly, the very young, and those with physiological or behavioral barriers to cooling, exertional heat stroke can occur in young, otherwise healthy individuals who generate metabolic heat from physical activity. Heat stroke can be fatal if body cooling is not rapidly initiated. Heat can also contribute to lung damage and pulmonary stress, particularly among those with underlying lung disease.[42] Heat and dehydration can affect complex cognitive function and skilled motor performance,[44] which can increase the risk of traumatic injuries via heat-induced fatigue and changes in balance, concentration, and behavior (Figure 2).[35,42]

Heat can also affect work capacity and productivity through its physiological effects. During the thermoregulatory response to excessive heat, enhanced blood flow to the skin can reduce the ability of muscles to perform physical work, and cardiopulmonary limitations can lead to reduced work pace.[31,45] Dehydration can compound the effects of heat on work capacity, and reductions in cognitive function and skilled motor performance can affect the pace and quality of work. Studies in laboratory settings suggest a 10% reduction in physical work capacity with mild heat stress (wet bulb globe temperature [WBGT], 18°C) and a 78% reduction with extreme heat (WBGT 40°C).[46–49] Chronic health effects of heat exposure may also affect the ability of individuals to work. Acute heat-related traumatic injuries may lead to permanent impairments. Chronic dehydration can lead to scarring of the kidneys (fibrosis) and may be a contributing cause of chronic kidney disease of unknown etiology, which has been reported in Mesoamerica, India, and other parts of the world,[50,51]

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

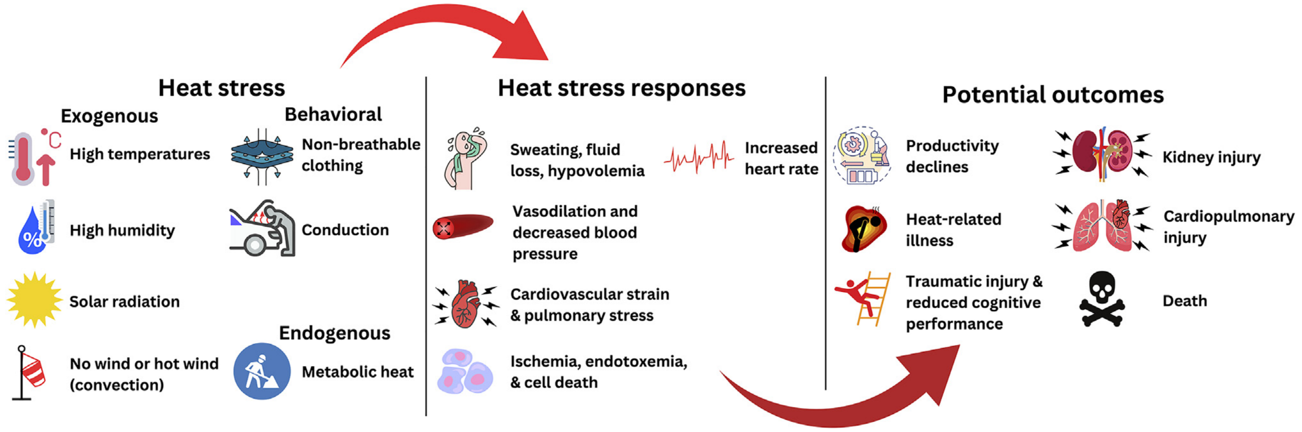

Figure 2. Mechanisms of heat-stress impact on health and well-being outcomes
The multiple components of heat stress, the channels through which heat stress impacts the human body, and outcomes that can emerge from excess heat stress. Heat-stress responses include normal physiological responses to maintain thermal equilibrium, which, when overwhelmed, can lead to tissue damage. Potential outcomes include both acute and long-term effects. Long-term effects may result from high-severity acute effects (e.g., severe heat stroke can lead to long-term organ damage; severe traumatic injury can lead to permanent impairment) or through repeated excess heat-exposure incidences (e.g., repeated kidney injury could contribute to chronic kidney disease).

necessitating renal replacement therapy (i.e., dialysis). Severe heat stroke can cause persistent brain, heart, kidney, liver, gastrointestinal, and lung damage, and an increased risk of subsequent mortality.[46]

When workers cannot perform work in cooler environments, health guidelines recommend decreasing work pace and intensity to reduce heat stress.[34,49,52] Additional recommended adaptations include providing water, rest, shade, and physiological acclimatization. Physiological acclimatization is an improvement in heat tolerance resulting from repeated physical activity over days to weeks in hot real-world settings (versus "acclimation" in laboratory settings).[53] It involves a greater maximum sweat rate, increased skin blood flow, reduced cardiovascular strain, improved fluid balance, and lower body temperature. The magnitude of acclimatization depends on the intensity, duration, and frequency of physical activity in the heat and environmental conditions.[53,54] On average, acclimatization may protect from an additional 2.5°C–3°C WBGT of exposure.[49] There is individual variability in heat acclimatization, but specific individual predictors of this variability are not comprehensively understood,[55] and the full extent of physiological adaptations in different populations and work settings remain uncharacterized. In humid environments, sweat evaporation is limited and may trigger compensation to try to maintain thermoregulation: for example, circulatory adaptations through a higher skin vapor pressure, which requires a higher skin temperature and higher skin blood flow, if cardiac capacity and hydration status allow.[53] The contribution of individual physiological acclimatization to net heat adaptation among workers in the tropics is yet to be comprehensively described but is expected to be bounded by human physiological capacity, with some variability from individual to individual.[15]

Assessing the heat impacts and the effectiveness of adaptation strategies and health guidelines for people in diverse contexts and occupations in the tropics is challenging for several reasons. First, there is a lack of studies performed in low- and middle-income countries, particularly in areas that are both hot and humid.[56] Second, there are discrepancies between laboratory studies, small-scale field studies, and population-based epidemiologic studies. Human physiological studies in climate chambers and energy-balance models indicate increased heat stress through decreased sweat evaporation during exposure to high humidity, using mass-based measures of the amount of moisture in the air (e.g., specific humidity, dew-point temperature, vapor pressure, absolute humidity). However, population-scale epidemiologic studies, predominantly in higher-income countries, have reported mixed results of the effect of humid heat on health outcomes among general and non-occupational populations. Rather than mass-based measures, epidemiologic studies often use humidity variables with a thermal component (e.g., relative humidity) or combined temperature/humidity indices (e.g., heat index [a function of temperature and relative humidity] or WBGT[57]). In addition to differences in humidity metrics, populations, and geography, the discrepancy between laboratory and epidemiologic findings may result from inadequate interpretations of the relationship between temperature and humidity, sub-daily phenomena (e.g., rain) resulting in biased results of studies based on daily data, and assessment of populations with pre-existing impairments in sweating, inactivity, or reduced hydration and, thus, sweating capacity.[56]

Methods underlying occupational heat health recommendations and research often are not derived from observations of workers in the tropics. Research modeling impacts of heat exposure and climate change on worker health and productivity builds upon foundational laboratory research on safe heat-exposure thresholds and observational studies of the relationship between heat exposure and outcomes in other settings. For example, WBGT thresholds for safe heat exposure in published guidelines, such as the National Institute for Occupational Safety and Health (NIOSH) heat criteria document and American Conference of Governmental Industrial Hygienists Heat Stress Threshold Limit Value, are based on studies of core body temperature in laboratory participants who generally were not living in the tropics.[34,49] Small-scale field studies among workers

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

typically assess key factors that are associated with physiological effects of heat, including clothing, workload, environmental heat exposure (i.e., air temperature, radiant heat, humidity, and air movement, for example with a composite metric such as WBGT), and acclimatization status. Furthermore, recent laboratory analyses,[58] which involved physiological observations of young, healthy adult participants in the northeastern United States performing modest metabolic rate work, have challenged "first principles" physiology guidance for safe human upper-limit wet bulb temperature (T_w) thresholds. Vecellio et al.[58] identified uncompensable heat stress in laboratory participants significantly below the previously recommended 35°C T_w threshold,[59] which varied significantly with humidity, showing that a single threshold is insufficient. However, the study did not include acclimatized participants from the tropics.[3,58]

A shortcoming of the existing body of research is the lack of key insights into how humid heat impacts specific populations and occupational groups in the tropics. Furthermore, there is limited research on whether existing guidelines are applicable in all occupational settings in the tropics (for relevant reviews see Flouris et al.[15] and Ioannou et al;[22]). However, a focus on general modifiable factors provides relevant information on potential actions that may increase adaptive capacity, as well as decrease exposures and vulnerabilities, across different contexts and occupations. These actions can be further prioritized and refined as new and more directly relevant research emerges.

CLIMATE AND LAND-USE CHANGE IMPACTS ON HUMID HEAT

The planet is already experiencing the effects of approximately 1.3°C of global warming (relative to the pre-industrial era),[60] and heat and humidity levels in the global tropics are much closer to human tolerance thresholds than anywhere else on Earth.[59] There are three main drivers of increasing temperatures in the tropics: global climate change, local land-use change, and local urbanization. Current trends for all three factors in the tropics indicate that heat impacts will be exacerbated in the future.[3,4,27,61–63]

According to worker safety standards,[34,49,52,64] during many daylight hours much of the tropics was already hot and humid enough that thresholds for safe heavy work (metabolic rate of ~415 W; corresponding to threshold value of 26.5°C WBGT) were surpassed during the last two decades. Consequently, even acclimatized workers wearing light clothing should be limiting their work time to a fraction of an hour (Figure 3A). Under future global warming, temperature and specific humidity over tropical land areas are projected to increase.[2,68] Climate models show local humid heat (e.g., T_w, WBGT) over tropical land areas will increase at about 0.8°C–1.4°C per degree of global warming[70,71] during all months of the year, regardless of warming scenario (Figure S1; Parsons et al.[68]). Therefore, under even an additional 0.5°C–1°C of global warming, outdoor workers will be affected by both the spatial expansion and increased proportion of daylight (work) hours that exceed safe heat-exposure thresholds (Figures 3B and 3C).

To quantify population exposure with ~1°C of global warming, we used 2001–2020 climate data and 2010 population statistics. We estimated approximately 1% of the population (range due to interannual climate variability: 0.06%–2.35%) resides in places where heavy work needed to be restricted for over half of the year's hours (Figure 3D). This corresponds to approximately 8 million people (range: 3–141 million) with significant lost work time in the last decade. Population exposure in the tropics substantially increases at ~2°C of global warming (assuming moderate population growth under Shared Socioeconomic Pathway 2 [SSP2] in 2050), with about 13% of the population (range due to interannual variability: 8.4%–21.2%), or approximately 797 million people (range: 505–1,273 million), located in areas where heavy work should be limited for over half of the hours in the year (Figure 3D). Countries with particularly severe impact under additional global warming include Bahrain, Cambodia, Pakistan, Qatar, and the UAE, which are projected to lose up to 10%–15% of labor productivity by about 3°C of global warming.[72] In terms of economic (GDP) losses, humid heat is projected to most strongly impact countries in tropical West Africa and South and Southeast Asia, with some countries showing losses equivalent to 3%–5% of GDP.[72]

The most significant recent deforestation has occurred predominantly in the tropics.[73] Tropical deforestation, driven primarily by conversion of land for agricultural use,[74] is a major driver of increased local heat exposure. The conversion warms the local land surface up to several degrees Celsius due to the loss of cooling.[25,30,75–78] As trees are lost, local daytime temperatures rise, increasing the likelihood of outdoor workers losing safe working time during the day.[3,4,27,30] Temperature increases are greater where forest loss is more spatially extensive.[25,79,80] Beyond local temperature changes associated with deforestation, increases in maximum temperatures can be found up to tens of kilometers away from deforested regions.[79,80] Tropical deforestation is projected to continue and even to intensify in many countries in the coming decades (Figure 3A; Popp et al.[81]). Climate model simulations from the Community Earth System Model[82] indicate that forest-to-cropland conversion will exacerbate humid heat stress in most of these locations (hatching in shaded areas in Figure 4A).

Tropical deforestation has also been shown to impact climate beyond changing local temperatures; for example, influencing rainfall.[85,86] Removal and subsequent burning of biomass in the tropics (i.e., tropical deforestation) increases atmospheric CO_2 levels, contributing to global warming. For example, tropical deforestation constituted approximately 7%–14% of total anthropogenic CO_2 emissions from 2000 to 2005,[87] and deforestation continues to be an important component of anthropogenic emissions.[88] Furthermore, complete deforestation of various rainforests has also been shown to impact local and remote climate in climate-modeling experiments.[89,90]

In addition to deforestation and global climate change, urbanization is exposing more people in the tropics to high temperatures. Urban areas are characterized by impervious surfaces in place of natural land cover and increased heat storage and reduced cooling effects of vegetation from evapotranspiration and shading.[91–93] As a result, urban areas experience higher temperatures compared to surrounding rural areas, a phenomenon known as the urban heat island (UHI) effect.[94] Urbanization is expected to lead to large increases in urban areas in the

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

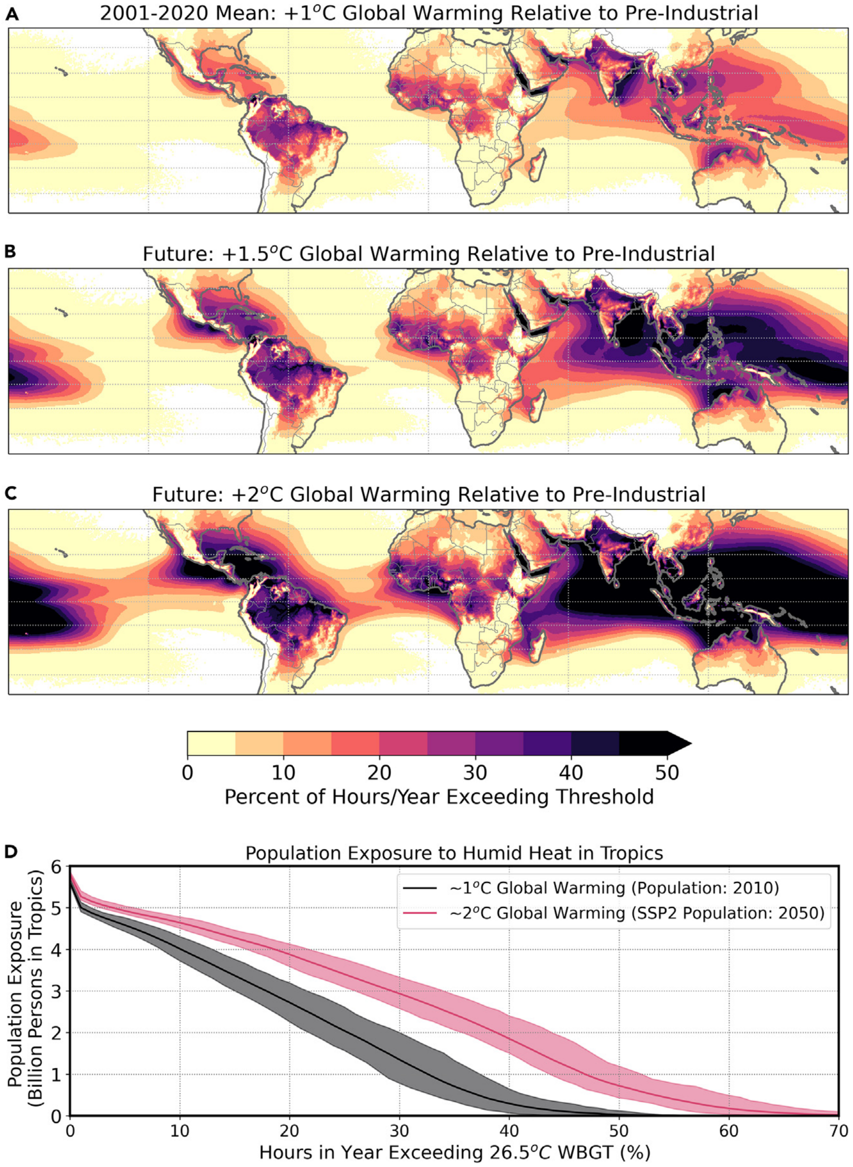

Figure 3. Percent of time and total population in locations where the wet bulb globe temperature (WBGT) exceeds the limit reference value, above which the International Organization of Standardization (ISO) suggests limiting the allowed heavy working time to a fraction of each work hour

Percent of time refers to the average number of hours per year that exceed the limit reference value (WBGT of 26.5°C) for all days of the year.

(A) Percent of time for the years 2001–2020, a time period with about 1°C of global warming relative to the pre-industrial.

(B) Percent of time exceeding this threshold in a world with 1.5°C of global warming (expected in 2030, 5%–95%: 2021–2040[65]) relative to the pre-industrial era.

(C) Percent of time exceeding this threshold in a world with 2°C of global warming (expected in 2052, 5%–95%: 2037–2084[65]) relative to the pre-industrial era.

(D) Percent of population in the tropics in locations where WBGT exceeds the 26.5°C threshold. Population data from 2010 are used to estimate historical exposure (2001–2020) at 1°C of global warming relative to the pre-industrial era, and 2050 Shared Socioeconomic Pathway 2 (SSP2) population projections for 2050 are used for estimating projected exposure at 2°C of global warming. Shading around the lines shows the range of impacts associated with interannual climate variability around the 20-year mean, which is shown with a dark line.

WBGT is calculated from reanalysis data[66] using the method of Brimicombe et al.[67] Climate model monthly warming patterns (Figure S1) used to assess future changes under 1.5°C and 2°C of warming are from Parsons et al.[68] A threshold (limit reference value) of 26.5°C WBGT is used here. Above a WBGT of ∼26°C–26.5°C, both the ISO and NIOSH standards suggest that heavy work (metabolic rate of ∼415 W) for acclimatized workers wearing light work clothes should be limited to a fraction of an hour.[34,64,69].

coming decades (Figure 4B), especially in countries in the (already hot) tropics.[95,96] The magnitude and even the direction of the UHI effect varies across eco-climatic regions, with generally larger effects observed for cities in moist climates (e.g., forest biomes), smaller effects in drier climates, and very low or even negative effects in desert cities,[94,97,98] though only during daytime.[93] Globally, urbanization has resulted in large increases in summer heat exposure that are compounded by climate-change impacts on local temperatures,[99–104] especially in the tropics.[102] Urbanization also has been found to contribute substantially to increases in the intensity of temperature extremes and heat waves as well as to increased heat stress[94,100] and humid heat stress, especially in wet climates and coastal areas.[84] Continuing urbanization in the coming decades (Figure 4B) is expected to intensify UHI effects, leading to additional warming similar in magnitude to that induced by future global climate change, with the largest increases in UHIs in temperate and tropical regions.[95] Shaded regions in Figure 4B show where the SSP2 scenario projects future urban expansion, with modeled increases in daily average urban humid heat stress shown in hatching. Regions showing increases in urban humid heat stress and projected urban expansion include discrete areas in the Americas, portions of sub-Saharan Africa, and large parts of South and East Asia (Figure 4B).

A combination of factors, including background weather and climate, land cover, and irrigation methods, can magnify or reduce local heat stress in urban and more rural agricultural areas. Specifically, irrigation can reduce local land surface temperatures via enhanced evapotranspiration[105–107] but increase humid heat exposure.[108] Irrigation in cities in dry climates can make cities cooler than their surroundings,[109] with about 60% of urban areas in India experiencing a daytime urban cool island effect. By contrast, in agricultural areas, although irrigation reduces land surface temperature during the crop-growing season,[105,106] it increases soil moisture, which in turn enhances humid heat stress.[108] In addition, irrigation also reduces atmospheric aridity and increases soil moisture and relative

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

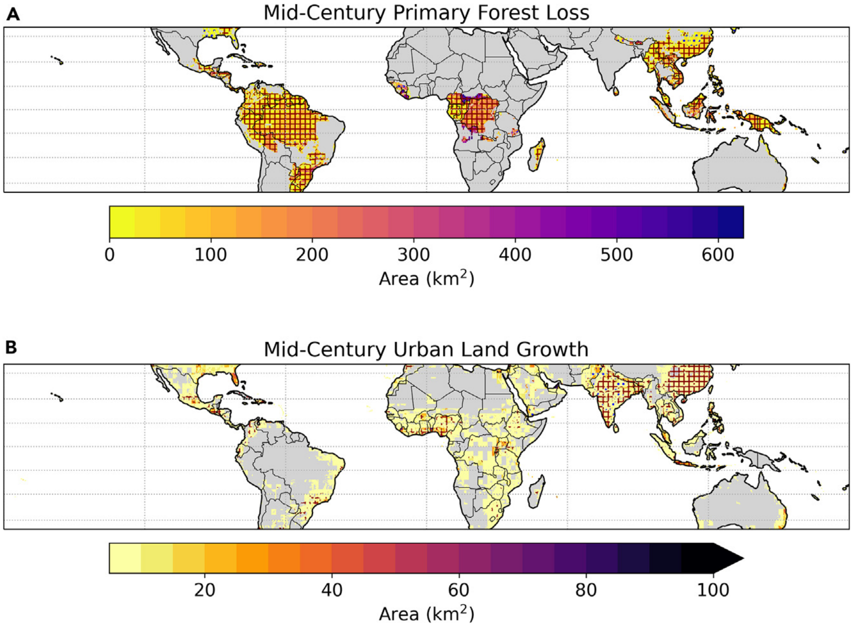

Figure 4. Projected mid-century primary forest loss and urban land growth across the tropics in SSP2 and associated changes in humid heat stress

(A) Projected loss in primary forest cover between 2015–2025 and 2055–2065 with modeled increases (hatching) and decreases (blue dots) in humid heat stress associated with cropland conversion.

(B) Projected increase in urban area between 2015–2025 and 2055–2065 with modeled increases (hatching) and decreases (blue dots) in humid heat stress associated with urban heat island effects.

Locations with less than 0.1 km^2 of projected change per ~625 km^2 are shown in gray. Projected land-use and cover data on a 0.25° spatial grid are from the University of Maryland Land Use Harmonization (LUH-2) dataset used in the SSPs.[81] According to International Energy Agency estimates, SSP2 is currently the scenario that aligns most closely with pledged and projected emissions for the next several decades.[83] Modeled changes in urban heat island humid heat stress are from Zhang et al.[84] Modeled changes in humid heat stress associated with cropland conversion are from Orlov et al.[82]

humidity.[110] In regions such as India, where humid heat stress typically occurs during the pre-monsoon and monsoon seasons (April–August), reducing irrigation-intensive crops (e.g., rice and maize) could reduce humid heat stress in the region. Additionally, improving the water-use efficiency of irrigation (e.g., sprinkler and drip) could reduce humid heat stress and water use from flood irrigation, a commonly employed irrigation method.[111–113]

HUMID HEAT AND OUTDOOR WORKERS IN THE TROPICS

In the tropics, approximately 1.2 billion working-age (15–64 years old) people work in outdoor industries, such as agriculture, forestry, fisheries, and construction, according to combined statistics from the International Labor Organization (ILO)[114] and global working-age population data.[115] The large-scale changes described in the previous section (global climate change and local land-use changes) have already led to significant impacts that will be further amplified over the century due to projected population growth.

In much of Africa, South Asia, and Southeast Asia, over 50% of workers are in outdoor industries (Figure S2B) that are already exposed to high heat, and future population growth will magnify impacts in many countries, particularly in Africa. The majority of workers are in agriculture, fisheries, and forestry in most of sub-Saharan Africa, South and Southeast Asia, and Andean South America, whereas similar or larger numbers work in construction in several countries with higher per-capita GDP in the Middle East, North Africa, and Brazil (Figures S2B–S2D). Many of the countries with large dependence on agriculture, forestry, and fisheries have large working-age populations, resulting in millions to hundreds of millions of exposed workers in some low-latitude countries (Figure S2A). Several of these countries are also likely to experience large population increases over the next few decades, especially those in Africa (Figures 5 and S2E). This combination of factors suggests that the impacts of increasing humid heat (Figure S1) on outdoor workers will likely affect the largest number of people in tropical Africa and Asia. Both of these regions already experience among the highest levels of humid heat exposure of any location, as illustrated by annual average maximum WBGT (Figure S2F). Specifically in Africa, countries with particularly high projected population growth and outdoor worker humid heat exposure include Niger, Malawi, Uganda, Liberia, Burkina Faso, and Nigeria (Figure 5). In Asia, Bahrain, Pakistan, Bangladesh, India, the Philippines, and Indonesia all show future positive population growth and current high humid heat exposure (Figure 5). Although the estimated and projected impacts of humid heat on outdoor workers in the tropics are significant (e.g., Parsons et al.[2] estimate up to 650 billion hours per year of lost potential heavy labor productivity associated with humid heat in the shade in recent years), evidence on exposure, adaptive capacity, and broader impacts remains inconsistent.

The lack of heat-impact estimates for specific sectors highlights a key gap in existing syntheses of heat impacts on outdoor workers in the tropics. ILO reports[7] and other publications[1] have highlighted the potential impacts of heat on labor productivity and wages, but they typically focus only on the agriculture, construction, industry, and service sectors, likely because country-level statistics from the ILO or World Bank are only available for a limited number of sectors. Compared to terrestrial workers, there is limited evidence on the impacts of humid heat exposure on the health and productivity of fishery and aquaculture workers[116–119]; even the ILO World Employment Report[120] does not include fishery sector workers in their assessment. Exposure to humid heat is exacerbated by direct sun exposure[121] and onboard temperatures that can be 10°C–20°C warmer than the ambient environment.[122] Additionally, coastal and ocean environments bring unique compounding occupational and environmental health exposures alongside humid

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

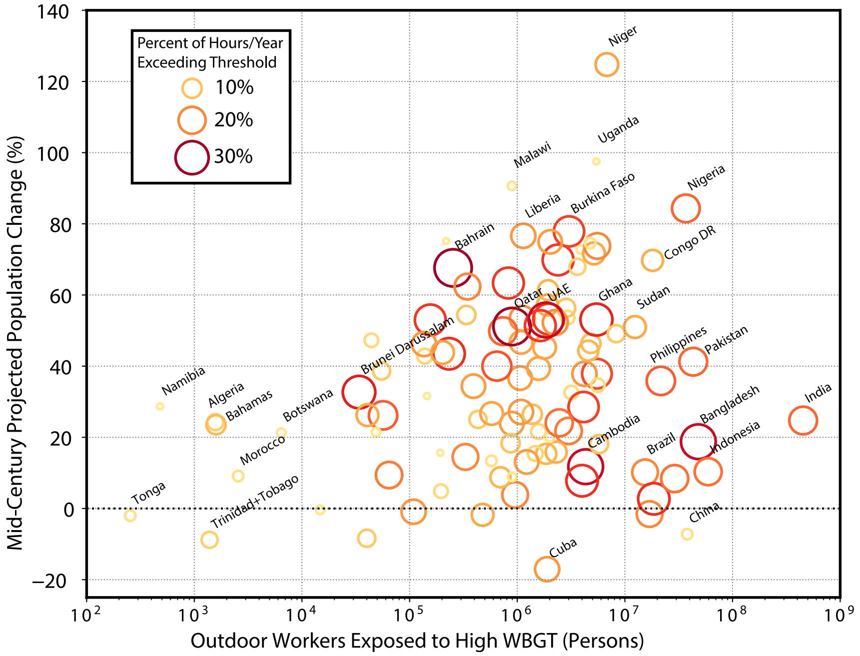

Figure 5. Country-level current humid heat exposure for outdoor workers and projected mid-century population growth

The number of working-age outdoor workers within each tropical country where average annual maximum WBGT exceeds 26.5°C. Country-level population change projected in the year 2050 relative to the year 2020 in SSP2 (a mid-growth scenario). The size of the circles corresponds to the population-weighted average number of hours (at present day) that exceed the 26.5°C WBGT threshold discussed in the text. Larger circles and darker colors highlight countries in which more hours currently exceed this threshold. Note the log scale on the x axis. WBGT 2001–2020 calculated from hourly reanalysis data (Hersbach et al.[66]) using the method of Brimicombe et al.[67] Above a WBGT of ∼26°C–26.5°C, both ISO and NIOSH standards suggest that heavy work (metabolic rate of ∼415 W) for acclimatized workers wearing light work clothes should be limited to a fraction of an hour.

heat, including tropical disease,[123] harmful algal blooms,[124] increasing storminess,[125] and shifting and degrading fish stocks that can create longer working shifts at sea and riskier behaviors.[126,127] Of the estimated 113 million people worldwide who are employed along small-scale fisheries value chains or engaged in subsistence activities, the vast majority are located in Asia (81.9%; primarily China and India) and Africa (12.0%).[128] Despite these risks, comparatively little research measures and maps exposure, estimates health impacts, and illuminates the diversity of working conditions for non-terrestrial outdoor workers.

Our own estimates indicate that currently (2001–2020 at ∼1°C of global warming) about 0.1% of land and ocean area in the tropics is hot and humid enough that standards suggest heavy work for acclimatized workers wearing light work clothes should be limited to a fraction of an hour for at least half of all hours (or 4,380 h) in the year (Figure 3A). Under just 1.5°C of global warming (expected in 2030, 5%–95%: 2021–2040[65]), 1.1% of the tropics exceed this threshold for over half of the hours in the year. At ∼2°C of global warming (expected in 2052, 5%–95%: 2037–2084[65]), over 16% of the tropics exceeds this threshold for at least half of all hours in the year (Figure 3C). In terms of population-weighted average exposure to hours of unsafe work in the tropics, our own estimates indicate that for the average person in the tropics, ∼19% of all hours in the year exceed this threshold currently. Under an additional 1°C of global warming, ∼28% of all hours in the year exceed this threshold for the average person in the tropics.

Large-scale and sectoral evidence of heat impacts masks the way in which key demographic and identity traits influence the working conditions, exposures, and impacts from humid heat. Individual qualities, such as gender, age, and ethnicity, shape physiological and behavioral responses to humid heat.[22] Heat dissipation may take longer for women as compared to men,[129] and exposure to humid heat stress can be further compounded by lower hourly wages and unhygienic sanitation facilities that deter women from taking breaks to rehydrate.[130,131] Age also affects the impact of heat exposure on workers, with the elderly and those with chronic diseases having reduced heat tolerance and thermoregulatory responses.[132–134] Minoritized communities may be less likely to seek or have access to medical assistance to cope with impacts from humid heat stress.[135,136] Moving beyond an assessment of humid heat impacts on different labor sectors requires an assessment of how individual characteristics moderate stress and behavior. Greater attention to heterogeneous impacts is necessary, and field-based studies are particularly well positioned to advance understanding of how humid heat impacts workers, accounting for contextual and individual factors.

ADAPTATION AND ADAPTIVE CAPACITY

A limitation of the impact-based studies reviewed above is that they rarely identify or address worker adaptations to hot environments in the tropics. In this section, we focus on two aspects of adaptation to heat at the individual level: (1) the range of autonomous adaptations and (2) the drivers of adaptive capacity.

One type of adaptation to working in hot environments is individual adaptation, which is autonomous in nature,[137] enacted intuitively within a cultural context rather than learned through institutional programs—so-called everyday adaptations.[32] Individuals' and households' adaptation behaviors are primarily driven by their perceptions rather than objective measures of temperature.[30,138–141] The adaptation literature documents a spectrum of strategies (Figure 6), such as decreasing activities that have increased heat exposure (e.g., Masuda et al.[30]), shifting to new livelihood strategies,[137] increasing reliance on remittances from household members that have migrated,[143–145] increasing labor mobility,[146] and, more drastically, moving the entire household to new geographies.[147] Individuals, for example, may intuitively adapt to heat by going to air-conditioned spaces on hot days to cool off[148] or by rotating work to

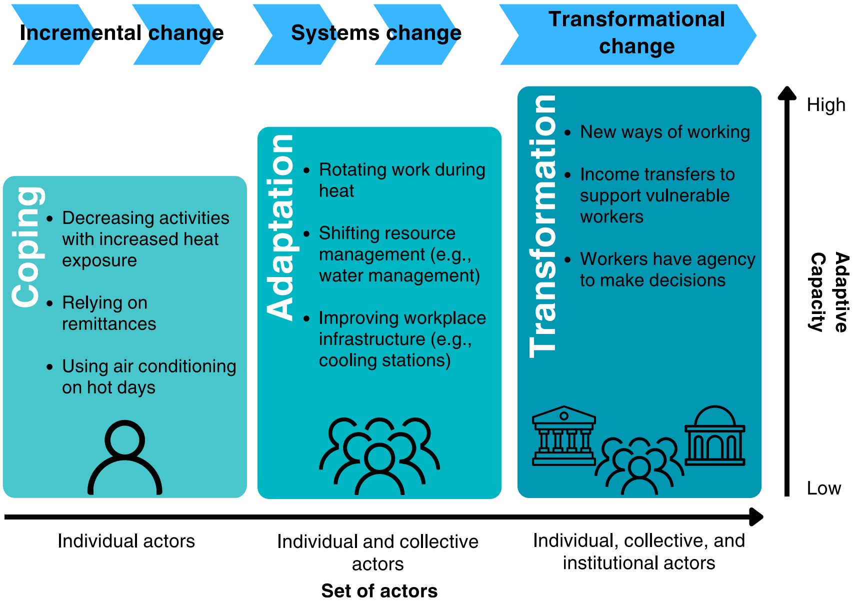

Figure 6. Spectrum of adaptation strategies in response to extreme heat

Adaptation to extreme heat occurs across a spectrum. The first set of adaptations are coping strategies. These are strategies individual actors use to reduce their exposure to extreme heat. Such strategies involve behavior changes that help individuals cope with extreme heat in the moment and often occur as incremental changes. As extreme heat becomes more common, individual and collective actors enact adaptation strategies that not only help them cope with extreme heat but also reduce exposure to extreme heat over time. These adaptations create systems change through adaptations to working patterns, resource management (e.g., timing of planting crops, water management), and/or workplace infrastructure changes (e.g., cooling stations). Transformational adaptation strategies are radical interventions[142] that strategically transform social and economic systems to reduce long-term impacts of extreme heat over time by reducing individuals' vulnerability and exposure to extreme heat. Each progressive set of adaptation strategies across this spectrum requires higher levels of adaptive capacity among individuals, collectives, and institutions to be successfully and sustainably enacted.

balance the impacts of more strenuous tasks on hot days.[149] The subtleties of such autonomous adaptations are difficult to anticipate and estimate through impact studies of temperature changes and labor productivity, and whether adaptations are maladaptive or improve resilience is often unpredictable.[150]

Individual factors such as gender and age constrain adaptation options in addition to the constraints they place on physiological and behavioral responses to heat discussed in the previous section. Men and women in the same household often enact different adaptations aligned with cultural and social norms.[151] An intrahousehold study in rural Kenya showed that wives more often adopt crop-related adaptation strategies whereas husbands enact livestock and agroforestry adaptation efforts.[152] These adaptation strategies align with gendered responsibilities within households. For example, when Kenyan women are responsible for producing food and ensuring nutrition for household members, they adapt household habits in response to food insecurity.[152] This and other studies of rural farming households also find differences in how men and women access capital; female farmers in Kenya have more access to social capital than their male counterparts,[153] while male farmers more readily have access to financial capital (i.e., credit), given property rights and other legal or customary rules.[154–157] These individual factors can limit adaptation options according to cultural norms. For example, in many countries where women lack inheritance rights and land ownership rights, they may be unable to obtain loans to engage in new livelihood strategies that reduce heat exposure. Addressing such disparities thus holds promise for promoting more equitable adaptation even when accounting for the effects of individual factors on physiological and behavioral responses to heat.

Overall, much of the documented evidence on adaptations to heat in the tropics is based on studies of agricultural livelihoods.[137] Here, studies find that smallholder farmers have adapted to multiple climate impacts via land management, irrigation, changing farming calendars, and water harvesting[152,158–161] as well as shifting the timing of farming activities (e.g., planting), using more drought-tolerant and early-maturing crop varieties and planting fruit trees that increase shade.[162]

In the absence of technical interventions at institutional, infrastructural, and ecosystem levels and rapid reductions in emissions, behavioral adaptive responses in specific contexts will reach physiological limits.[163] For example, a simple but effective strategy to increase adaptive capacity is to minimize exposure to hot work environments in some industries by shifting time of work to cooler times of the day when possible. By the end of the century, however, on average 5.7 h of work time will need to be shifted from current daytime schedules to offset lost labor during normal daytime hours.[164] As global temperatures rise, employers and workers will lose the ability to move labor to the historically cooler early-morning hours of the day because these hours also become too hot and humid for continuous work.[68] The decline in productivity and income from having to work less mean this strategy will ultimately reach its limit.

These adaptation limits can be stretched through actions focusing on modifiable factors to increase the adaptive capacity of workers and limit damage, particularly among workers with low adaptive capacity.[153] Improving access to and control over natural and financial capital by private companies, non-governmental organizations, and governments can improve individuals' and households' adaptive capacity.[165,166] Indeed, land tenuring can increase workers' natural capital and thereby their adaptive capacity[167] because it can increase the agency of landowners, such as through investment in alternative livelihoods, access to credit, and less reliance on resources bought at markets (e.g., firewood).[168–171] Individual-level adaptation limits could be stretched through the mechanization of outdoor work. Models show that autonomous mechanization of outdoor work in the agricultural and construction sectors has the potential to improve heat-induced reductions in worker productivity and, thereby, economic losses.[172]

Additionally, adaptations at the level of governments and employers that incorporate the pre-existing daily habits and

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

Table 1. Illustrative set of possible solutions by actors and types of solutions

Potential solutions			
Actor	Primary	Secondary	Tertiary
Government	● policies focused on greenhouse gas emissions reductions or increased CO_2 sequestration, urban greening, and those supportive of sustainable and resilient land uses (e.g., preventing further deforestation, regulations around sustainable irrigation practices)	● public service campaigns to support implementation of policies and best practices to recognize and appropriately respond to workers with symptoms caused by workplace heat stress	● workers' compensation, rehabilitative, vocational, and financial benefits (may also be offered through private workers' compensation systems)
	● development and enforcement of occupational safety & health and labor regulations that include provisions to reduce worker heat stress and enhance preventive measures (e.g., shade, rest breaks, work-shift timing, advance awareness of weather conditions, and written heat-stress prevention plans)	● enforcement of occupational policy provisions requiring identification and response to health effects of heat stress	
	● public service campaigns to support implementation of policies and best practices to reduce worker heat stress and enhance adaptive capacity	● reduction of barriers to healthcare access for workers suffering from symptoms caused by workplace heat stress	
	● grants to support employment transitions for workers seeking to reduce reliance on work involving excess humid heat exposure		
Community and household	● development and dissemination by community-based organizations of tailored worker heat-stress prevention training and tools to support best practices for heat-stress prevention and awareness of rights for different work settings and populations	● training and education by community-based organizations for workers and community health workers about recognition of, and response to, symptoms of heat illness and other health effects of heat stress	● monetary or in-kind community assistance to aid in basic household needs for households with recovering workers
	● assistance available through informal networks or through community groups, such as community savings associations (e.g., microcredit loans) to aid in transitioning to less heat-exposed livelihoods		
Employer	● training, education, and workplace policies for workers and supervisors covering recognition of, and response to, symptoms of heat illness and other health effects of heat stress	● implementation of occupational heat policies and best practices to reduce worker heat stress and enhance adaptive capacity (e.g., flexible work schedules, rest breaks, cooling stations)	● accommodation of medical restrictions for workers recovering from heat-related illnesses and injuries
			● paid time off, sick days, and medical assistance if workers fall ill or are injured from excess heat exposure, when workers' compensation benefits are not available

(*Continued on next page*)

Table 1. *Continued*

	Potential solutions		
Actor	Primary	Secondary	Tertiary
Individual	• implementation of heat-stress prevention best practices (e.g., clothing options that are least likely to retain heat, adequate hydration), following training and with employer support	• implementation of training on high-heat procedures, including timely and appropriate identification, reporting, and cooling of co-workers suffering from health effects of heat stress	• pursuit of opportunities to shift to livelihood strategies that eliminate or drastically reduce heat exposures in the future

These examples provide potential actions taken to adapt or mitigate heat impacts for outdoor workers and do not represent a comprehensive accounting of actions. Primary solutions are those that focus on actions that proactively reduce heat stress or enhance adaptive capacity; secondary solutions focus on actions that can be taken during heat stress to reduce risks of impacts; and tertiary actions are those that can be taken after heat stress to reduce the severity of impacts.

routines of individuals within impacted communities will have a higher likelihood of improving resilience and leading to greater uptake.[32,173] At times, formal adaptation strategies can disrupt local everyday adaptation strategies by being contrary to cultural preferences or livelihood routines, thereby reducing rather than enhancing adaptive capacity.[174] Support for autonomous adaptations, the most common responses to humid heat, are critical. Strategies to support autonomous adaptations include social protection programs,[175] providing access to shaded or forested work areas,[30,176] and the strategic reduction of adaptation barriers.[177] Reducing structural barriers at work through regulations or employer policies can also support autonomous adaptations. These include anticipating heat events using appropriate metrics, addressing acclimatization, scheduling breaks, shifting working hours, and encouraging a moderated work pace during heat events.

The existing body of research on individual adaptation to extreme heat lacks comprehensive categorization and quantification of the diverse autonomous adaptation actions of outdoor workers. Furthermore, research in outdoor work sectors beyond agricultural livelihoods remains limited. However, this research provides relevant information on how individual adaptations are shaped by socioeconomic characteristics, gender, and household dynamics, among other factors, that decrease exposures in agricultural contexts that potentially apply in other contexts and occupations. These individual actions can be supported by and aligned with adaptation measures across scales to reduce outdoor workers' vulnerability and exposure to extreme heat in a more targeted, and therefore effective, manner.

TOWARD SOLUTIONS TO MITIGATE HEAT IMPACTS ON WORKERS

The preceding sections provide grounding for insights on solutions to mitigate humid heat impacts on workers in the tropics. Modifiable factors vary by actors that operate along different temporal and spatial scales (Figure 1), where each actor has varying degrees of control over the type and range of actions they can take to mitigate adverse worker impacts. Here, we build on existing prevention frameworks from the public health literature to define primary, secondary, and tertiary solutions that can be enacted by various actors.[178] Primary solutions are actions that proactively reduce excess humid heat stress and enhance adaptive capacity. Secondary solutions are actions that aim to reduce risks of impacts during heat stress. Tertiary solutions mitigate the severity of impacts after heat stress has occurred and there are signs of adverse impacts. Within the spectrum of adaptation to mitigation (Figure 1), primary solutions can be seen as increasing adaptive capacity, while secondary and tertiary solutions can be characterized as aiding in active adaptation and mitigation of impacts. We provide an illustrative set of solutions given the actor and solution type in Table 1.

All actors can take steps toward implementing primary solutions across a broad spatial and temporal range. Primary solutions to reduce humid heat stress and enhance adaptive capacity align with the fundamental principle and right of workers to a safe and healthy work environment.[179] Governments in particular have an outsized role in fostering conditions that reduce worker heat stress through numerous channels, as broad-scale changes often rely on actions that are often outside the locus of control for individual workers (Figure 1B). Governments may enact ambitious emission-reduction targets that are supported by subsidies to foster energy transitions or increase adoption of climate-friendly agricultural practices, or they may impose taxes that incentivize reductions in the consumption of fossil fuels by businesses and consumers.[106] For example, nationally determined contributions are a focal point for ramping up ambitions for greenhouse gas reductions.[107] Such climate-change mitigation actions would ultimately reduce increases in worker heat exposure.

Government policies can also profoundly shape factors driving land-use change that can exacerbate heat extremes. For example, agricultural policies affect land-use choices, both directly and indirectly. Directly, agricultural subsidies influence crop and livestock choices, which in turn drive how much land farmers clear and manage for agricultural production.[180] Indirectly, global food systems can create incentives for large-scale land acquisitions (LSLAs) by investors and industrial agricultural companies,[181–184] which have been associated with significantly higher rates of deforestation.[185,186] In an analysis of carbon emissions from LSLAs among just a subset of land deals in 80 countries between 2000 and 2016, LSLAs are estimated to lead to up to 2.5 GtC of emissions.[184] Moratoria, such as those enacted in Indonesia,[187] have been found to decrease land conversion, highlighting the importance of government actors in

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

shaping broader land-use changes. Similarly, city leaders and planners determine urban density and expansion through zoning, infrastructure development, and other choices.[188]

Government actors can also advance primary solutions for working populations through workplace occupational safety and health and labor regulations. Regulations can include provisions to reduce worker heat stress, for example through shade and cooling stations, rest breaks, work-shift timing (i.e., avoidance of work during the hottest periods of the day), advance awareness of weather conditions, and documented heat-stress prevention plans. Effective policy implementation requires employer action, including support for supervisors and others responsible for day-to-day decision-making that affects worker health and safety, and appropriate policy enforcement. Competing policies should also be considered, such as those that disincentivize workers from taking breaks or reducing work pace (e.g., piece-rate payment schemes). Occupational health considerations should also be incorporated into jurisdictional heat action plans,[178] designed to outline strategies to reduce health impacts before, during, and after extreme heat events.

Communities and individual workers can additionally enact primary solutions. In addition to workplaces and governments, community and other non-governmental organizations can develop and disseminate worker heat-stress prevention training and tools that can be adapted to specific work settings and demographics of the workforce, along with information about how workers can exercise their rights. Following training and with employer support, workers can implement heat-stress prevention best practices, for example through selection of clothing options that are least likely to retain heat and through adequate hydration. Workers may also choose to work with their households and communities to pursue opportunities to decrease reliance on livelihoods that have disproportionate risks of excess exposure to humid heat. These opportunities could include assistance available through informal networks or through community groups, such as community savings associations (e.g., microcredit loans) to aid in transitioning to less heat-exposed livelihoods and government grants to support employment transitions.

Secondary solutions reduce heat impacts during excess heat stress. Governments, workplaces, and communities can advance secondary solutions by providing required and best practices training and education campaigns for workers, their supervisors, and community health workers focused on recognition of and response to symptoms of heat illness and other health effects of heat stress. Following implementation of primary solutions, including training and workplace heat-stress prevention plans, workplaces and workers can execute procedures that include timely and appropriate identification, reporting, and cooling of workers suffering from health effects of heat stress such as heat exhaustion and heat stroke. Governments should appropriately enforce required workplace heat-policy provisions, including identification and response to health effects of heat stress. Disproportionately affected communities may require greater outreach and structural changes (e.g., better healthcare access and elimination of discriminatory policies) to reduce barriers to seeking medical assistance when experiencing symptoms of heat stress.

Tertiary solutions mitigate the severity of heat impacts after heat stress and are relevant to all actors. Although worker benefits are likely rare or unavailable in low- and middle-income country settings, these tertiary solutions are particularly urgent given the need to elevate worker rights and defenses against heat. Government and private workers' compensation systems may provide rehabilitative, vocational, and financial resources for those that may be unable to work at their prior capacity due to permanent impairments or during recovery from heat illness or other health effects of occupational heat stress. Employers may also provide support in the form of paid time off, sick days, and medical assistance if workers fall ill or are injured from excess heat exposure. Employer accommodation of worker medical restrictions (e.g., light-duty work in a less hot environment) as they recover may also reduce the risk of long-term work disability.[189] Communities and households likely play an especially critical role in tertiary solutions in settings without strong worker rights or for workers in informal employment. They may leverage informal social networks and capital to receive assistance, such as other household members joining the labor force, or using shared community resources while a worker recovers from heat illness or injury. Workers may shift to livelihood strategies that eliminate or drastically reduce heat exposures in the future, although this presumes sufficient capital and technical knowledge that may not be readily available. The core aim of tertiary solutions is to soften the long-term impacts that stem from excess heat stress, which may range from health impacts (e.g., heat illness, heat-related traumatic injury, kidney injury), financial impacts (e.g., reduced productivity and incomes), or other adverse impacts.

Ideal solution packages will span primary, secondary, and tertiary categories. For example, information about climate-change impacts and adaptation choices could, if presented in an accessible manner, enhance workers' adaptive capacity by laying the foundation for informed action, supporting adaptation as heat exposure is occurring and mitigating damages that have occurred. Shrimp farmers in coastal Bangladesh have more accurate short-term perceptions of climate impacts than long-term.[190] In this case, providing objective climate information to workers could improve adaptive capacity by addressing cognitive biases and limitations, thus avoiding sole reliance on perceptions when making choices about adaptive behaviors.[162,191,192] Technical assistance and access to financial and other resources to aid in diversifying livelihoods can occur before, during, and after heat-exposure impacts. Ultimately, if the aim is to safeguard and bolster worker health and well-being (which includes outcomes beyond just a worker's physical health), simultaneously implementing primary, secondary, and tertiary solutions is necessary for reducing heat impacts.

FUTURE RESEARCH DIRECTIONS

Our synthesis of the current and future impacts of heat reinforces findings that, in the absence of rapid reductions in greenhouse gas emissions and changes in land use, there are likely substantial limits to bolstering worker resilience to hot environments despite the variety of creative solutions that various actors can adopt. As the world warms and the frequency and intensity of extreme heat events increase, three key considerations warrant

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

further study. First is that a worker's overall adaptive capacity supports (and is supported by) his or her household, and more work is needed to understand how factors outside a worker's own needs drive adaptation. For example, adaptations to heat impacts on agricultural households, such as temporary migration and adopting climate-resilient livelihoods, are likely informed by overall household needs and are not solely a response to working in hot environments.[193] At the same time, social policies that provide free childcare or education to children of outdoor workers would mitigate exposure to excessive heat by reducing the immediate financial pressure on families. Greater options and reduced financial pressure during extreme heat increase workers' adaptive capacity and, thereby, resilience. Further work should examine how intra-household dynamics shape worker choice and behavior as they relate to worker well-being and how such choices can be integrated into models that estimate heat impacts at large scales.

Second, more work is needed to understand broader worker impacts and adaptations in the face of multiple climate stressors (i.e., droughts, floods, wildfires, tropical cyclones) and broader environmental change (e.g., habitat and biodiversity loss), and whether and how adaptation strategies available to workers and other actors are severely constrained by compounding threats. Recent reviews, for example, have found that each climate impact presents additional challenges to workers and households.[137] We are unaware of analyses of co-exposures among representative populations (e.g., fishers, farmers, construction workers) in the tropics, which others have highlighted as needing further study.[17,194] Furthermore, questions remain about the physiological effects of multiple climate stressors on workers, how best to anticipate and monitor for them, quantifying whether there are tradeoffs or synergies in adaptation strategies to various stressors (e.g., wearing non-breathable clothing to protect against pesticide exposure but increasing risk of humid heat impacts), and the various interactions that co-exposures (e.g., heat and air pollution) may have on worker health and productivity in the tropics.

Finally, more work is needed on maladaptation, i.e., unintended adverse consequences stemming from adaptation choices.[150,195–198] Maladaptation is best conceptualized as a spectrum[150] and results from both intentional and autonomous adaptive choices taken by all actors. For example, workers may migrate to areas less prone to hot and humid work environments (e.g., moving from agricultural work in low-lying areas to forestry work done at higher elevations), but do so in exchange for new climate and socioeconomic vulnerabilities such as landslide risk at higher elevations or fewer livelihood opportunities in new locations. Employers may enact policies to shift work to cooler hours but simultaneously introduce hazards related to poor lighting or insufficient sleep. Governments may mandate employers to cease working during extreme heat events, but this may drive workers supporting households with immediate needs to the informal sector where there may be fewer formal rights and protections. Maladaptations can also occur across scales. Increasing demand for air-conditioning, for example, will generate greater energy demand, which may lead to more greenhouse gas emissions,[199,200] ultimately exacerbating a key driver of ambient heat (Figure 1). Systematic documentation of maladaptations by workers, households, communities, employers, and governments is lacking, suggesting that this is a particularly high-need research area, as a confluence of interests has increasingly highlighted the importance of bolstering the resilience of workers and communities in the tropics.[201–205] It may also be possible to mitigate potential adverse effects of maladaptations, thus rendering them viable options.

DISCUSSION

Ambient humid heat in the tropics is already a widespread problem for outdoor workers (Figures 3A and 3D), and projected land-use change (Figure 4) and population growth in this region (Figure 5) will likely exacerbate risks. Focusing on modifiable factors to reduce worker vulnerability and resilience to heat can help reorient discussions to specific actions as well as to the many uncertainties that still exist around how to mitigate and adapt to humid heat. Our framework (Figure 1 and Table 1) captures a broad range of actions, which can range from reducing fossil fuel emissions and adopting sustainable land uses, to employer-specific actions such as providing more rest breaks, to worker-specific actions such as adopting new livelihoods with less heat exposure, if practical and possible. This broad perspective differs from other reviews (e.g., Ioannou et al.[22] and Morris et al.[206]) that focused on workers and/or employers by emphasizing the actors and timescales most likely to successfully implement these actions.

Ideally, multiple primary, secondary, and tertiary actions can simultaneously be implemented to optimize worker health and well-being. For instance, governments could institute early-warning systems for heat events as part of heat action plans and regulations to mandate employers to provide cool-down rest areas or cooling stations, sufficient rest breaks, flexible work schedules, schedules to acclimatize new workers, and stop work activities during extreme heat events. Households could diversify income streams to reduce reliance on jobs with significant exposures to hot environments. If supported by workplace and government policies, workers could be educated on a broader suite of strategies when working in hot environments.[206] Further work is needed to evaluate specific strategies in real-world settings characterized by humid heat, as these approaches may differ from those recommended in dry heat settings, to inform prioritization of the most promising approaches.[56] A key question that remains underexplored is the relative effectiveness of different adaptive actions in the tropics, whether their effectiveness varies by population, and the complementary actions that can be taken by various actors to bolster workers' immediate and long-term resilience to heat. In the medium and long term, however, the most effective action would be to rapidly reduce greenhouse gas emissions to slow global warming, as this is the underlying large-scale driver of increasing heat exposure for workers in the tropics. Furthermore, at subnational scales, stopping large-scale tropical deforestation will be critical for preventing immediate local heat extremes.[3,4,25,26,78]

Even in pro-labor contexts, workers often face constraints to employ even a subset of actions to support heat health best practices. An obvious barrier hindering workers' agency is the uneven power dynamics between employers and employees. Raising awareness about heat health practices will do little to ameliorate heat stress if workers are worried about stable employment or

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

retaliation. Employers often dictate the timing and duration of work and breaks, and employers can indirectly pressure employees to work longer and at higher intensities due to inherent power imbalances.[207] Power dynamics depend on context and employment structure—self-employed or subsistence workers may possess greater agency than workers in formal contexts. For instance, on family farms, even when workers are incentivized to work longer and at a higher intensity, they may choose to work more slowly and reduce productivity or shift their work schedule because they have greater agency (i.e., adaptive capacity) than in industrial farm settings to adjust their work behavior in response to hot environments.[30,31] Another constraint is that choices are inherently limited by cost, sustainability, and other factors.[206] Providing individual shade and cooling devices to workers in agricultural fields may be technically possible, but they are unlikely to be implemented at large scales if they are cost-prohibitive or otherwise unfeasible. Another complicating factor arises when, even if employers and employees agree on reducing heat impacts, they may have contrasting preferences regarding priority heat defenses.[206] Future efforts to coordinate and harmonize actions by various actors should be cognizant of the financial tradeoffs, diverse interests, varying incentives, and limits each actor has in the types of actions they can take to support the reduction of heat impacts on workers in the tropics.

CONCLUSION

Throughout our review, a common theme across the four bodies of evidence is that workers in the tropics face a dire future of increased exposure, higher sensitivity, and limited adaptive capacity. Addressing modifiable factors can directly reduce ambient heat exposure (e.g., air-conditioning, adjusting work timing to cooler parts of the day, land-use planning, and better-planned built environments), reduce internal heat generation (e.g., rest breaks, reductions in work pace), allow for heat dissipation (e.g., use of breathable clothing), and create structural factors that support workers (e.g., reducing disincentives to take breaks or reduce work pace).[34] Workers are a key pillar supporting households and communities. Alongside rapid emissions reduction, mobilizing policy and research to identify the extent to which modifiable factors can bolster the resilience of workers across sectors, demographic groups, and locations in the tropics is urgent.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2024.02.001.

ACKNOWLEDGMENTS

Funding from Battelle provided support for N.H.W. and L.A.P., as well as for open access publishing.

AUTHOR CONTRIBUTIONS

Y.J.M. and L.A.P. supervised and designed the research. Y.J.M., L.A.P., J.T.S., D.S.B., B.C., J.T.E., E.T.G., T.G., P.K., T.K., V.M., D.S., M.T., L.R.V.Z., and N.H.W. conducted the synthesis, drafted the manuscript, and reviewed and revised the paper.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Romanello, M., Di Napoli, C., Drummond, P., Green, C., Kennard, H., Lampard, P., Scamman, D., Arnell, N., Ayeb-Karlsson, S., Ford, L.B., et al. (2022). The 2022 report of the Lancet Countdown on health and climate change: health at the mercy of fossil fuels. Lancet *400*, 1619–1654. https://doi.org/10.1016/S0140-6736(22)01540-9/ATTACHMENT/D63703F8-315E-4CDB-9573-1E552E1D4913/MMC5.PDF.
2. Parsons, L.A., Masuda, Y.J., Kroeger, T., Shindell, D., Wolff, N.H., and Spector, J.T. (2022). Global labor loss due to humid heat exposure underestimated for outdoor workers. Environ. Res. Lett. *17*, 014050. https://doi.org/10.1088/1748-9326/ac3dae.
3. Wolff, N.H., Zeppetello, L.R.V., Parsons, L.A., Aggraeni, I., Battisti, D.S., Ebi, K.L., Game, E.T., Kroeger, T., Masuda, Y.J., and Spector, J.T. (2021). The effect of deforestation and climate change on all-cause mortality and unsafe work conditions due to heat exposure in Berau, Indonesia: a modelling study. Lancet Planet. Health *5*, e882–e892. https://doi.org/10.1016/S2542-5196(21)00279-5.
4. Parsons, L.A., Jung, J., Masuda, Y.J., Vargas Zeppetello, L.R., Wolff, N.H., Kroeger, T., Battisti, D.S., and Spector, J.T. (2021). Tropical deforestation accelerates local warming and loss of safe outdoor working hours. One Earth *4*, 1730–1740. https://doi.org/10.1016/j.oneear.2021.11.016.
5. Vargas Zeppetello, L.R., Raftery, A.E., and Battisti, D.S. (2022). Probabilistic projections of increased heat stress driven by climate change. Commun. Earth Environ. *3*, 183. https://doi.org/10.1038/s43247-022-00524-4.
6. King, A.D., and Harrington, L.J. (2018). The inequality of climate change from 1.5 to 2°C of global warming. Geophys. Res. Lett. *45*, 5030–5033. https://doi.org/10.1029/2018GL078430.
7. Kjellstrom, T., Maître, N., Saget, C., Otto, M., and Karimova, T. (2019). Working on a Warmer Planet: The Effect of Heat Stress on Productivity and Decent Work.
8. United Nations Population Division (2019). World Population Prospects 2019.
9. FAO (2021). World Food and Agriculture – Statistical Yearbook 2021 (FAO). https://doi.org/10.4060/cb4477en.
10. Ohnsorge, F., and Yu, S. (2022). The Long Shadow of Informality: Challenges and Policies (The World Bank). https://doi.org/10.1596/978-1-4648-1753-3.
11. Bonnet, F., Vanek, J., and Chen, M. (2019). Women and Men in the Informal Economy – A Statistical Brief (WEIGO).
12. Barrett, C.B., Garg, T., and McBride, L. (2016). Well-Being Dynamics and Poverty Traps. Annu. Rev. Resour. Economics *8*, 303–327. https://doi.org/10.1146/annurev-resource-100815-095235.
13. Garg, T., Gibson, M., and Sun, F. (2020). Extreme temperatures and time use in China. J. Econ. Behav. Organ. *180*, 309–324. https://doi.org/10.1016/J.JEBO.2020.10.016.
14. Dasgupta, S., van Maanen, N., Gosling, S.N., Piontek, F., Otto, C., and Schleussner, C.-F. (2021). Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet. Planet. Health *5*, e455–e465. https://doi.org/10.1016/S2542-5196(21)00170-4.
15. Flouris, A.D., Dinas, P.C., Ioannou, L.G., Nybo, L., Havenith, G., Kenny, G.P., and Kjellstrom, T. (2018). Workers' health and productivity under occupational heat strain: a systematic review and meta-analysis. Lancet. Planet. Health *2*, e521–e531. https://doi.org/10.1016/S2542-5196(18)30237-7.
16. Kjellstrom, T., Briggs, D., Freyberg, C., Lemke, B., Otto, M., and Hyatt, O. (2016). Heat, Human Performance, and Occupational Health: A Key Issue for the Assessment of Global Climate Change Impacts. Annu. Rev. Public Health *37*, 97–112. https://doi.org/10.1146/annurev-publhealth-032315-021740.
17. Moda, H.M., Filho, W.L., and Minhas, A. (2019). Impacts of Climate Change on Outdoor Workers and Their Safety: Some Research Priorities. Int. J. Environ. Res. Public Health *16*, 3458. https://doi.org/10.3390/IJERPH16183458.
18. Ansah, E.W., Ankomah-Appiah, E., Amoadu, M., and Sarfo, J.O. (2021). Climate change, health and safety of workers in developing economies: A scoping review. The Journal of Climate Change and Health *3*, 100034. https://doi.org/10.1016/J.JOCLIM.2021.100034.

19. Ebi, K.L., Vanos, J., Baldwin, J.W., Bell, J.E., Hondula, D.M., Errett, N.A., Hayes, K., Reid, C.E., Saha, S., Spector, J., et al. (2021). Extreme Weather and Climate Change: Population Health and Health System Implications. Annual Review Of Public Health, 293–315. https://doi.org/10.1146/ANNUREV-PUBLHEALTH-012420-105026.

20. Fatima, S.H., Rothmore, P., Giles, L.C., Varghese, B.M., and Bi, P. (2021). Extreme heat and occupational injuries in different climate zones: A systematic review and meta-analysis of epidemiological evidence. Environ. Int. *148*, 106384. https://doi.org/10.1016/J.ENVINT.2021.106384.

21. Habibi, P., Moradi, G., Dehghan, H., Moradi, A., and Heydari, A. (2021). The impacts of climate change on occupational heat strain in outdoor workers: A systematic review. Urban Clim. *36*, 100770. https://doi.org/10.1016/J.UCLIM.2021.100770.

22. Ioannou, L.G., Foster, J., Morris, N.B., Piil, J.F., Havenith, G., Mekjavic, I.B., Kenny, G.P., Nybo, L., and Flouris, A.D. (2022). Occupational Heat Strain in Outdoor Workers: A Comprehensive Review and Meta-Analysis. Temperature *9*, 67–102. https://doi.org/10.1080/23328940.2022.2030634.

23. Kroeger, C. (2023). Heat is associated with short-term increases in household food insecurity in 150 countries and this is mediated by income. Nat. Hum. Behav. *7*, 1777–1786. https://doi.org/10.1038/s41562-023-01684-9.

24. Kong, Q., and Huber, M. (2022). Explicit Calculations of Wet-Bulb Globe Temperature Compared With Approximations and Why It Matters for Labor Productivity. Earth's Future *10*, e2021EF002334. https://doi.org/10.1029/2021EF002334.

25. Vargas Zeppetello, L.R., Parsons, L.A., Spector, J.T., Naylor, R.L., Battisti, D.S., Masuda, Y.J., and Wolff, N.H. (2020). Large scale tropical deforestation drives extreme warming. Environ. Res. Lett. *15*, 084012. https://doi.org/10.1088/1748-9326/ab96d2.

26. Prevedello, J.A., Winck, G.R., Weber, M.M., Nichols, E., and Sinervo, B. (2019). Impacts of forestation and deforestation on local temperature across the globe. PLoS One *14*, e0213368. https://doi.org/10.1371/journal.pone.0213368.

27. Alves de Oliveira, B.F., Bottino, M.J., Nobre, P., and Nobre, C.A. (2021). Deforestation and climate change are projected to increase heat stress risk in the Brazilian Amazon. Commun. Earth Environ. *2*, 207. https://doi.org/10.1038/s43247-021-00275-8.

28. Kjellstrom, T., Kovats, R.S., Lloyd, S.J., Holt, T., and Tol, R.S.J. (2009). The direct impact of climate change on regional labor productivity. Arch. Environ. Occup. Health *64*, 217–227. https://doi.org/10.1080/19338240903352776.

29. Kjellstrom, T., Freyberg, C., Lemke, B., Otto, M., and Briggs, D. (2018). Estimating population heat exposure and impacts on working people in conjunction with climate change. Int. J. Biometeorol. *62*, 291–306. https://doi.org/10.1007/s00484-017-1407-0.

30. Masuda, Y.J., Castro, B., Aggraeni, I., Wolff, N.H., Ebi, K., Garg, T., Game, E.T., Krenz, J., and Spector, J. (2019). How are healthy, working populations affected by increasing temperatures in the tropics? Implications for climate change adaptation policies. Glob. Environ. Change *56*, 29–40. https://doi.org/10.1016/j.gloenvcha.2019.03.005.

31. Masuda, Y.J., Garg, T., Anggraeni, I., Ebi, K., Krenz, J., Game, E.T., Wolff, N.H., and Spector, J.T. (2021). Warming from tropical deforestation reduces worker productivity in rural communities. Nat. Commun. *12*, 1601. https://doi.org/10.1038/s41467-021-21779-z.

32. Castro, B., and Sen, R. (2022). Everyday Adaptation: Theorizing climate change adaptation in daily life. Glob. Environ. Change *75*, 102555. https://doi.org/10.1016/J.GLOENVCHA.2022.102555.

33. National Institute for Occupational Safety and Health (2021). Worker Well-Being Questionnaire (WellBQ) | NIOSH | CDC. https://www.cdc.gov/niosh/twh/wellbq/default.html.

34. Jacklitsch, B.L., Williams, W.J., Musolin, K., Coca, A., Kim, J.-H., and Turner, N. (2016). Occupational Exposure to Heat and Hot Environments: Revised Criteria 2016 (National Institute for Occupational Safety and Health).

35. Spector, J.T., Masuda, Y.J., Wolff, N.H., Calkins, M., and Seixas, N. (2019). Heat Exposure and Occupational Injuries: Review of the Literature and Implications. Curr. Environ. Health Rep. *6*, 286–296. https://doi.org/10.1007/s40572-019-00250-8.

36. Nusinovici, S., Zhang, L., Chai, X., Zhou, L., Tham, Y.C., Vasseneix, C., Majithia, S., Sabanayagam, C., Wong, T.Y., and Cheng, C.Y. (2022). Machine learning to determine relative contribution of modifiable and non-modifiable risk factors of major eye diseases. Br. J. Ophthalmol. *106*, 267–274. https://doi.org/10.1136/BJOPHTHALMOL-2020-317454.

37. Maas, P., Barrdahl, M., Joshi, A.D., Auer, P.L., Gaudet, M.M., Milne, R.L., Schumacher, F.R., Anderson, W.F., Check, D., Chattopadhyay, S., et al. (2016). Breast Cancer Risk From Modifiable and Nonmodifiable Risk Factors Among White Women in the United States. JAMA Oncol. *2*, 1295–1302. https://doi.org/10.1001/JAMAONCOL.2016.1025.

38. Ho, F.K., Celis-Morales, C.A., Gray, S.R., Katikireddi, S.V., Niedzwiedz, C.L., Hastie, C., Ferguson, L.D., Berry, C., MacKay, D.F., Gill, J.M., et al. (2020). Modifiable and non-modifiable risk factors for COVID-19, and comparison to risk factors for influenza and pneumonia: results from a UK Biobank prospective cohort study. BMJ Open *10*, e040402. https://doi.org/10.1136/BMJOPEN-2020-040402.

39. Füssel, H.M., and Klein, R.J.T. (2006). Climate change vulnerability assessments: An evolution of conceptual thinking. Clim. Change *75*, 301–329. https://doi.org/10.1007/S10584-006-0329-3/METRICS.

40. IPCC (2014). In Climate Change 2014 – Impacts, Adaptation and Vulnerability: Regional Aspects, C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, and R.C. Genova, et al., eds. (Cambridge University Press).

41. Dodman, D., Sverdlik, A., Agarwal, S., Kadungure, A., Kothiwal, K., Machemedze, R., and Verma, S. (2023). Climate change and informal workers: Towards an agenda for research and practice. Urban Clim. *48*, 101401. https://doi.org/10.1016/J.UCLIM.2022.101401.

42. Ebi, K.L., Capon, A., Berry, P., Broderick, C., de Dear, R., Havenith, G., Honda, Y., Kovats, R.S., Ma, W., Malik, A., et al. (2021). Hot weather and heat extremes: health risks. Lancet *398*, 698–708. https://doi.org/10.1016/S0140-6736(21)01208-3.

43. Sawka, M.N., Leon, L.R., Montain, S.J., and Sonna, L.A. (2011). Integrated physiological mechanisms of exercise performance, adaptation, and maladaptation to heat stress. Compr. Physiol. *1*, 1883–1928. https://doi.org/10.1002/CPHY.C100082.

44. Masuda, Y.J., Garg, T., Anggraeni, I., Wolff, N.H., Ebi, K., Game, E.T., Krenz, J., and Spector, J.T. (2020). Heat exposure from tropical deforestation decreases cognitive performance of rural workers: an experimental study. Environ. Res. Lett. *15*, 124015. https://doi.org/10.1088/1748-9326/abb96c.

45. Sawka, M.N., Cheuvront, S.N., and Kenefick, R.W. (2012). High skin temperature and hypohydration impair aerobic performance. Exp. Physiol. *97*, 327–332. https://doi.org/10.1113/EXPPHYSIOL.2011.061002.

46. Foster, J., Smallcombe, J.W., Hodder, S., Jay, O., Flouris, A.D., Nybo, L., and Havenith, G. (2021). An advanced empirical model for quantifying the impact of heat and climate change on human physical work capacity. Int. J. Biometeorol. *65*, 1215–1229. https://doi.org/10.1007/s00484-021-02105-0.

47. D'Ambrosio Alfano, F.R., Malchaire, J., Palella, B.I., and Riccio, G. (2014). WBGT Index Revisited After 60 Years of Use. Ann. Occup. Hyg. *58*, 955–970. https://doi.org/10.1093/ANNHYG/MEU050.

48. Jacklitsch, B., Williams, W., Musolin, K., Coca, A., Kim, J.-H., and Turner, N. (2016). NIOSH Criteria for a Recommended Standard: Occupational Exposure to Heat and Hot Environments (US Department of Health and Human Services). Publication 2016-106.

49. ACGIH (2023). 2023 TLVs and BEIs (American Conference of Governmental Industrial Hygienists).

50. Redmon, J.H., Levine, K.E., Lebov, J., Harrington, J., and Kondash, A.J. (2021). A comparative review: Chronic Kidney Disease of unknown etiology (CKDu) research conducted in Latin America versus Asia. Environ. Res. *192*, 110270. https://doi.org/10.1016/J.ENVRES.2020.110270.

51. Lunyera, J., Mohottige, D., von Isenburg, M., Jeuland, M., Patel, U.D., and Stanifer, J.W. (2016). CKD of uncertain etiology: A systematic review. Clin. J. Am. Soc. Nephrol. *11*, 379–385. https://doi.org/10.2215/CJN.07500715/-/DCSUPPLEMENTAL.

52. ISO 7243:2017 - Ergonomics of the Thermal Environment — Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index. 2017. https://www.iso.org/standard/67188.html.

53. Périard, J.D., Racinais, S., and Sawka, M.N. (2015). Adaptations and mechanisms of human heat acclimation: Applications for competitive athletes and sports. Scand. J. Med. Sci. Sports *25* (*Suppl 1*), 20–38. https://doi.org/10.1111/SMS.12408.

54. Alkemade, P., Gerrett, N., Eijsvogels, T.M.H., and Daanen, H.A.M. (2021). Individual characteristics associated with the magnitude of heat acclimation adaptations. Eur. J. Appl. Physiol. *121*, 1593–1606. https://doi.org/10.1007/S00421-021-04626-3.

55. Corbett, J., Rendell, R.A., Massey, H.C., Costello, J.T., and Tipton, M.J. (2018). Inter-individual variation in the adaptive response to heat acclimation. J. Therm. Biol. *74*, 29–36. https://doi.org/10.1016/J.JTHERBIO.2018.03.002.

56. Baldwin, J.W., Benmarhnia, T., Ebi, K.L., Jay, O., Lutsko, N.J., and Vanos, J.K. (2023). Humidity's Role in Heat-Related Health Outcomes: A

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

Heated Debate. Environ. Health Perspect. *131*, 55001. https://doi.org/10.1289/EHP11807.

57. Steadman, R.G. (1979). The Assessment of Sultriness. Part I: A Temperature-Humidity Index Based on Human Physiology and Clothing Science. J. Appl. Meteor. *18*, 861–873. https://doi.org/10.1175/1520-0450(1979)018<0861:TAOSPI>2.0.CO;2.
58. Vecellio, D.J., Wolf, S.T., Cottle, R.M., and Kenney, W.L. (2022). Evaluating the 35C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project). J. Appl. Physiol. *132*, 340–345. https://doi.org/10.1152/JAPPLPHYSIOL.00738.2021/ASSET/IMAGES/LARGE/JAPPLPHYSIOL.00738.2021_F002.JPEG.
59. Sherwood, S.C., and Huber, M. (2010). An adaptability limit to climate change due to heat stress. Proc. Natl. Acad. Sci. USA *107*, 9552–9555. https://doi.org/10.1073/pnas.0913352107.
60. Wong, C. (2023). Earth just had its hottest year on record — climate change is to blame. Nature *623*, 674–675. https://doi.org/10.1038/D41586-023-03523-3.
61. Harrington, L.J., Frame, D.J., Fischer, E.M., Hawkins, E., Joshi, M., and Jones, C.D. (2016). Poorest countries experience earlier anthropogenic emergence of daily temperature extremes. Environ. Res. Lett. *11*, 055007. https://doi.org/10.1088/1748-9326/11/5/055007.
62. Mora, C., Counsell, C.W.W., Bielecki, C.R., and Louis, L.V. (2017). Twenty-seven ways a heat wave can kill you: Deadly heat in the era of climate change. Circ. Cardiovasc. Qual. Outcomes *10*, e004233. https://doi.org/10.1161/CIRCOUTCOMES.117.004233.
63. Zhang, Y., Held, I., and Fueglistaler, S. (2021). Projections of tropical heat stress constrained by atmospheric dynamics. Nat. Geosci. *14*, 133–137. https://doi.org/10.1038/s41561-021-00695-3.
64. Bröde, P., Fiala, D., Lemke, B., and Kjellstrom, T. (2018). Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric. Int. J. Biometeorol. *62*, 331–345. https://doi.org/10.1007/S00484-017-1346-9/METRICS.
65. Lee, J.-Y., Marotzke, J., Bala, G., Cao, L., Corti, S., Dunne, J.P., Engelbrecht, F., Fischer, E., Fyfe, J.C., Jones, C., et al. (2021). Future Global Climate: Scenario-Based Projections and Near-Term Information. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate ChangeScience Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergover, V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y.C.L. Goldfarb, M.I. Gomis, and M. Huang, et al., eds. (Cambridge University Press).
66. Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., et al. (2020). The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. *146*, 1999–2049. https://doi.org/10.1002/QJ.3803.
67. Brimicombe, C., Lo, C.H.B., Pappenberger, F., Di Napoli, C., Maciel, P., Quintino, T., Cornforth, R., and Cloke, H.L. (2023). Wet Bulb Globe Temperature: Indicating Extreme Heat Risk on a Global Grid. Geohealth *7*, e2022GH000701. https://doi.org/10.1029/2022GH000701.
68. Parsons, L.A., Shindell, D., Tigchelaar, M., Zhang, Y., and Spector, J.T. (2021). Increased labor losses and decreased adaptation potential in a warmer world. Nat. Commun. 12, 7286.
69. ISO/DIS 7243 Ergonomics of the Thermal Environment— Assessment of Heat Stress Using the WBGT (Wet Bulb Globe Temperature) Index.
70. Buzan, J.R., and Huber, M. (2020). Moist Heat Stress on a Hotter Earth. Annu. Rev. Earth Planet. Sci. *48*, 623–655. https://doi.org/10.1146/annurev-earth-053018-060100.
71. Schwingshackl, C., Sillmann, J., Vicedo-Cabrera, A.M., Sandstad, M., and Aunan, K. (2021). Heat Stress Indicators in CMIP6: Estimating Future Trends and Exceedances of Impact-Relevant Thresholds. Earth's Future *9*, e2020EF001885. https://doi.org/10.1029/2020EF001885.
72. Saeed, W., Haqiqi, I., Kong, Q., Huber, M., Buzan, J.R., Chonabayashi, S., Motohashi, K., and Hertel, T.W. (2022). The Poverty Impacts of Labor Heat Stress in West Africa Under a Warming Climate. Earth's Future *10*, e2022EF002777. https://doi.org/10.1029/2022EF002777.
73. Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., et al. (2013). High-resolution global maps of 21st-century forest cover change. Science *342*, 850–853. https://doi.org/10.1126/science.1244693.
74. Curtis, P.G., Slay, C.M., Harris, N.L., Tyukavina, A., and Hansen, M.C. (2018). Classifying drivers of global forest loss. Science *361*, 1108–1111. https://doi.org/10.1126/SCIENCE.AAU3445/SUPPL_FILE/AAU3445_CURTIS_SM.PDF.
75. Lawrence, D., Coe, M., Walker, W., Verchot, L., and Vandecar, K. (2022). The Unseen Effects of Deforestation: Biophysical Effects on Climate. Front. For. Glob. Change *5*, 756115. https://doi.org/10.3389/FFGC.2022.756115/BIBTEX.
76. Ellison, D., Morris, C.E., Locatelli, B., Sheil, D., Cohen, J., Murdiyarso, D., Gutierrez, V., Noordwijk, M.v., Creed, I.F., Pokorny, J., et al. (2017). Trees, forests and water: Cool insights for a hot world. Glob. Environ. Change *43*, 51–61. https://doi.org/10.1016/j.gloenvcha.2017.01.002.
77. Bright, R.M., Davin, E., O'Halloran, T., Pongratz, J., Zhao, K., and Cescatti, A. (2017). Local temperature response to land cover and management change driven by non-radiative processes. Nat. Clim. Chang. *7*, 296–302. https://doi.org/10.1038/nclimate3250.
78. Alkama, R., and Cescatti, A. (2016). Biophysical climate impacts of recent changes in global forest cover. Science *351*, 600–604. https://doi.org/10.1126/science.aac8083.
79. Cohn, A.S., Bhattarai, N., Campolo, J., Crompton, O., Dralle, D., Duncan, J., and Thompson, S. (2019). Forest loss in Brazil increases maximum temperatures within 50 km. Environ. Res. Lett. *14*, 084047. https://doi.org/10.1088/1748-9326/ab31fb.
80. Crompton, O., Corrêa, D., Duncan, J., and Thompson, S. (2021). Deforestation-induced surface warming is influenced by the fragmentation and spatial extent of forest loss in Maritime Southeast Asia. Environ. Res. Lett. *16*, 114018. https://doi.org/10.1088/1748-9326/AC2FDC.
81. Popp, A., Calvin, K., Fujimori, S., Havlik, P., Humpenöder, F., Stehfest, E., Bodirsky, B.L., Dietrich, J.P., Doelmann, J.C., Gusti, M., et al. (2017). Land-use futures in the shared socio-economic pathways. Glob. Environ. Change *42*, 331–345. https://doi.org/10.1016/J.GLOENVCHA.2016.10.002.
82. Orlov, A., De Hertog, S., Havermann, F., Guo, S., Luo, F., Manola, I., Thiery, W., Lejeune, Q., Pongratz, J., Humpenöder, F., et al. (2023). Changes in Land Cover and Management Affect Heat Stress and Labor Capacity. Earth's Future *11*, e2022EF002909. https://doi.org/10.1029/2022EF002909.
83. Hausfather, Z., and Peters, G.P. (2020). Emissions – the 'business as usual' story is misleading. Nature *577*, 618–620. https://doi.org/10.1038/d41586-020-00177-3.
84. Zhang, K., Cao, C., Chu, H., Zhao, L., Zhao, J., and Lee, X. (2023). Increased heat risk in wet climate induced by urban humid heat. Nature *617*, 738–742. https://doi.org/10.1038/s41586-023-05911-1.
85. Garcia-Carreras, L., and Parker, D.J. (2011). How does local tropical deforestation affect rainfall? Geophys. Res. Lett. *38*, 19802. https://doi.org/10.1029/2011GL049099.
86. Smith, C., Baker, J.C.A., and Spracklen, D.V. (2023). Tropical deforestation causes large reductions in observed precipitation. Nature *615*, 270–275. https://doi.org/10.1038/s41586-022-05690-1.
87. Harris, N.L., Brown, S., Hagen, S.C., Saatchi, S.S., Petrova, S., Salas, W., Hansen, M.C., Potapov, P.V., and Lotsch, A. (2012). Baseline map of carbon emissions from deforestation in tropical regions. Science *336*, 1573–1576. https://doi.org/10.1126/SCIENCE.1217962/SUPPL_FILE/HARRIS-SOM.PDF.
88. Friedlingstein, P., O'sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P., et al. (2022). Global Carbon Budget 2022. Earth Syst. Sci. Data *14*, 4811–4900. https://doi.org/10.5194/ESSD-14-4811-2022.
89. Lawrence, D., and Vandecar, K. (2015). Effects of tropical deforestation on climate and agriculture. Nat. Clim. Chang. *5*, 27–36. https://doi.org/10.1038/nclimate2430.
90. De Hertog, S.J., Havermann, F., Vanderkelen, I., Guo, S., Luo, F., Manola, I., Coumou, D., Davin, E.L., Duveiller, G., Lejeune, Q., et al. (2022). The biogeophysical effects of idealized land cover and land management changes in Earth system models. Earth Syst. Dyn. *13*, 1305–1350. https://doi.org/10.5194/ESD-13-1305-2022.
91. Paschalis, A., Chakraborty, T., Fatichi, S., Meili, N., and Manoli, G. (2021). Urban Forests as Main Regulator of the Evaporative Cooling Effect in Cities. AGU Advances *2*, e2020AV000303. https://doi.org/10.1029/2020AV000303.
92. Venter, Z.S., Chakraborty, T., and Lee, X. (2021). Crowdsourced air temperatures contrast satellite measures of the urban heat island and its mechanisms. Sci. Adv. *7*, eabb9569. https://doi.org/10.1126/SCIADV.ABB9569/SUPPL_FILE/SCIADV.ABB9569_SM.PDF.
93. Chakraborty, T., and Lee, X. (2019). A simplified urban-extent algorithm to characterize surface urban heat islands on a global scale and examine vegetation control on their spatiotemporal variability. Int. J. Appl. Earth Obs. Geoinf. *74*, 269–280. https://doi.org/10.1016/J.JAG.2018.09.015.
94. Qian, Y., Chakraborty, T.C., Li, J., Li, D., He, C., Sarangi, C., Chen, F., Yang, X., and Leung, L.R. (2022). Urbanization Impact on Regional

Climate and Extreme Weather: Current Understanding, Uncertainties, and Future Research Directions. Adv. Atmos. Sci. *39*, 819–860. https://doi.org/10.1007/S00376-021-1371-9.

95. Huang, K., Li, X., Liu, X., and Seto, K.C. (2019). Projecting global urban land expansion and heat island intensification through 2050. Environ. Res. Lett. *14*, 114037. https://doi.org/10.1088/1748-9326/AB4B71.
96. Gao, J., and O'Neill, B.C. (2020). Mapping global urban land for the 21st century with data-driven simulations and Shared Socioeconomic Pathways. Nat. Commun. *11*. 2302-12. https://doi.org/10.1038/s41467-020-15788-7.
97. Fan, C., Myint, S., Kaplan, S., Middel, A., Zheng, B., Rahman, A., Huang, H.P., Brazel, A., and Blumberg, D. (2017). Understanding the Impact of Urbanization on Surface Urban Heat Islands—A Longitudinal Analysis of the Oasis Effect in Subtropical Desert Cities. Rem. Sens. *9*, 672. https://doi.org/10.3390/RS9070672.
98. Imhoff, M.L., Zhang, P., Wolfe, R.E., and Bounoua, L. (2010). Remote sensing of the urban heat island effect across biomes in the continental USA. Remote Sens. Environ. *114*, 504–513. https://doi.org/10.1016/J.RSE.2009.10.008.
99. Wu, X., Wang, L., Yao, R., Luo, M., Wang, S., and Wang, L. (2020). Quantitatively evaluating the effect of urbanization on heat waves in China. Sci. Total Environ. *731*, 138857. https://doi.org/10.1016/J.SCITOTENV.2020.138857.
100. Wang, J., Chen, Y., Liao, W., He, G., Tett, S.F.B., Yan, Z., Zhai, P., Feng, J., Ma, W., Huang, C., and Hu, Y. (2021). Anthropogenic emissions and urbanization increase risk of compound hot extremes in cities. Nat. Clim. Chang. *11*, 1084–1089. https://doi.org/10.1038/s41558-021-01196-2.
101. Tuholske, C., Caylor, K., Funk, C., Verdin, A., Sweeney, S., Grace, K., Peterson, P., and Evans, T. (2021). Global urban population exposure to extreme heat. Proc. Natl. Acad. Sci. USA *118*, e2024792118. https://doi.org/10.1073/PNAS.2024792118/SUPPL_FILE/PNAS.2024792118.SAPP.PDF.
102. Marcotullio, P.J., Keßler, C., and Fekete, B.M. (2021). The future urban heat-wave challenge in Africa: Exploratory analysis. Glob. Environ. Change *66*, 102190. https://doi.org/10.1016/J.GLOENVCHA.2020.102190.
103. Kedia, S., Bhakare, S.P., Dwivedi, A.K., Islam, S., and Kaginalkar, A. (2021). Estimates of change in surface meteorology and urban heat island over northwest India: Impact of urbanization. Urban Clim. *36*, 100782. https://doi.org/10.1016/J.UCLIM.2021.100782.
104. Chapman, S., Watson, J.E.M., Salazar, A., Thatcher, M., and McAlpine, C.A. (2017). The impact of urbanization and climate change on urban temperatures: a systematic review. Landsc. Ecol. *32*, 1921–1935. https://doi.org/10.1007/S10980-017-0561-4/METRICS.
105. Ambika, A.K., and Mishra, V. (2019). Observational Evidence of Irrigation Influence on Vegetation Health and Land Surface Temperature in India. Geophys. Res. Lett. *46*, 13441–13451. https://doi.org/10.1029/2019GL084367.
106. Thiery, W., Visser, A.J., Fischer, E.M., Hauser, M., Hirsch, A.L., Lawrence, D.M., Lejeune, Q., Davin, E.L., and Seneviratne, S.I. (2020). Warming of hot extremes alleviated by expanding irrigation. Nat. Commun. *11*, 290. https://doi.org/10.1038/s41467-019-14075-4.
107. Mueller, N.D., Butler, E.E., Mckinnon, K.A., Rhines, A., Tingley, M., Holbrook, N.M., and Huybers, P. (2015). Cooling of US Midwest summer temperature extremes from cropland intensification. Nat. Clim. Chang. *6*, 317–322. https://doi.org/10.1038/nclimate2825.
108. Mishra, V., Ambika, A.K., Asoka, A., Aadhar, S., Buzan, J., Kumar, R., and Huber, M. (2020). Moist heat stress extremes in India enhanced by irrigation. Nat. Geosci. *13*, 722–728. https://doi.org/10.1038/s41561-020-00650-8.
109. Kumar, R., Mishra, V., Buzan, J., Kumar, R., Shindell, D., and Huber, M. (2017). Dominant control of agriculture and irrigation on urban heat island in India. Sci. Rep. *7*, 14054. https://doi.org/10.1038/s41598-017-14213-2.
110. Ambika, A.K., and Mishra, V. (2020). Substantial decline in atmospheric aridity due to irrigation in India. Environ. Res. Lett. *15*, 124060. https://doi.org/10.1088/1748-9326/ABC8BC.
111. Dangar, S., and Mishra, V. (2023). Excessive pumping limits the benefits of a strengthening summer monsoon for groundwater recovery in India. One Earth *6*, 419–427. https://doi.org/10.1016/J.ONEEAR.2023.03.005.
112. Asoka, A., Gleeson, T., Wada, Y., and Mishra, V. (2017). Relative contribution of monsoon precipitation and pumping to changes in groundwater storage in India. Nat. Geosci. *10*, 109–117. https://doi.org/10.1038/ngeo2869.
113. Ambika, A.K., and Mishra, V. (2022). Improved Water Savings and Reduction in Moist Heat Stress Caused by Efficient Irrigation. Earth's Future *10*, e2021EF002642. https://doi.org/10.1029/2021EF002642.
114. ILO (2023). ILOSTAT - the Leading Source of Labour Statistics. https://ilostat.ilo.org/.
115. Center for International Earth Science Information Network (2018). Documentation for the Gridded Population of the World, Version 4 (GPWv4),Revision 11 Data Sets. https://doi.org/10.7927/H45Q4T5F.
116. Alayyannur, P.A., Ramdhan, D.H., and Tejamaya, M. (2023). Environmental Factors that are at Risk of Heat Stress Exposure to Fishermen in Indonesia. The Indonesian Journal of Occupational Safety and Health *12*, 20–24.
117. Aruna, N., and Kumar, V. (2023). Occupational Health Hazards of Marine Fishermen in Cuddalore District of Tamil Nadu-An Empirical Analysis. BioGecko *12*, 245–249.
118. Woodhead, A.J., Abernethy, K.E., Szaboova, L., and Turner, R.A. (2018). Health in fishing communities: A global perspective. Fish Fish. *19*, 839–852. https://doi.org/10.1111/FAF.12295.
119. Quandt, S.A., Kucera, K.L., Haynes, C., Klein, B.G., Langley, R., Agnew, M., Levin, J.L., Howard, T., and Nussbaum, M.A. (2013). Occupational health outcomes for workers in the agriculture, forestry and fishing sector: Implications for immigrant workers in the southeastern US. Am. J. Ind. Med. *56*, 940–959. https://doi.org/10.1002/AJIM.22170.
120. ILO (2020). World Employment and Social Outlook Trends 2020 ILO Flagship Report.
121. Cavalli, L.S., Marques, F.B., and Watterson, A. (2020). A critical overview of work-related injury and illness in aquaculture workers from Brazil. Rev Aquac *12*, 1157–1164. https://doi.org/10.1111/RAQ.12377.
122. Palella, B.I., Quaranta, F., and Riccio, G. (2016). On the management and prevention of heat stress for crews onboard ships. Ocean Eng. *112*, 277–286. https://doi.org/10.1016/J.OCEANENG.2015.12.030.
123. Escovar, J.E., González, R., and Quiñones, M.L. (2013). Anthropophilic biting behaviour of Anopheles (Kerteszia) neivai Howard, Dyar & Knab associated with Fishermen's activities in a malaria-endemic area in the Colombian Pacific. Mem. Inst. Oswaldo Cruz *108*, 1057–1064. https://doi.org/10.1590/0074-0276130256.
124. Grattan, L.M., Holobaugh, S., and Morris, J.G. (2016). Harmful algal blooms and public health. Harmful Algae *57*, 2–8. https://doi.org/10.1016/J.HAL.2016.05.003.
125. Sainsbury, N.C., Genner, M.J., Saville, G.R., Pinnegar, J.K., O'Neill, C.K., Simpson, S.D., and Turner, R.A. (2018). Changing storminess and global capture fisheries. Nat. Clim. Chang. *8*, 655–659. https://doi.org/10.1038/s41558-018-0206-x.
126. ILO (2013). Forced Labour and Trafficking in Fisheries Caught at Sea.
127. Sainsbury, N.C., Schuhmann, P.W., Turner, R.A., Grilli, G., Pinnegar, J.K., Genner, M.J., and Simpson, S.D. (2021). Trade-offs between physical risk and economic reward affect fishers' vulnerability to changing storminess. Glob. Environ. Change *69*, 102228. https://doi.org/10.1016/J.GLOENVCHA.2021.102228.
128. FAO, and Duke, U.; WorldFish (2023). Illuminating Hidden Harvests - the Contributions of Small-Scale Fisheries to Sustainable Development (FAO). https://doi.org/10.4060/cc4576en.
129. Venugopal, V., Rekha, S., Manikandan, K., Latha, P.K., Vennila, V., Ganesan, N., Kumaravel, P., and Chinnadurai, S.J. (2016). Heat stress and inadequate sanitary facilities at workplaces–an occupational health concern for women? Glob. Health Action *9*, 31945. https://doi.org/10.3402/GHA.V9.31945/SUPPL_FILE/ZGHA_A_11820799_SM0001.PDF.
130. Burdon, C.A., Johnson, N.A., Chapman, P.G., and O'Connor, H.T. (2012). Influence of Beverage Temperature on Palatability and Fluid Ingestion During Endurance Exercise: A Systematic Review. Int. J. Sport Nutr. Exerc. Metab. *22*, 199–211. https://doi.org/10.1123/IJSNEM.22.3.199.
131. McKinnon, M., Buckle, E., Gueye, K., Toroitich, I., Ionesco, D., Mach, E., and Maiero, M. (2016). Climate Change and Labour: Impacts of Heat in the Workplace.
132. Kenney, W.L., and Hodgson, J.L. (1987). Heat tolerance, thermoregulation and ageing. Sports Med. *4*, 446–456. https://doi.org/10.2165/00007256-198704060-00004.
133. Flouris, A.D., McGinn, R., Poirier, M.P., Louie, J.C., Ioannou, L.G., Tsoutsoubi, L., Sigal, R.J., Boulay, P., Hardcastle, S.G., and Kenny, G.P. (2018). Screening criteria for increased susceptibility to heat stress during work or leisure in hot environments in healthy individuals aged 31–70 years. Temperature *5*, 86–99. https://doi.org/10.1080/23328940.2017.1381800/SUPPL_FILE/KTMP_A_1381800_SM2708.PDF.
134. Carrillo, A.E., Flouris, A.D., Herry, C.L., Notley, S.R., Macartney, M.J., Seely, A.J.E., Wright Beatty, H.E., and Kenny, G.P. (2019). Age-related

reductions in heart rate variability do not worsen during exposure to humid compared to dry heat: A secondary analysis*6*, pp. 341–345. https://doi.org/10.1080/23328940.2019.1684791.

135. Li, H., Guan, J., Ye, H., and Yang, H. (2019). A Survey of Rural Residents' Perception and Response to Health Risks from Hot Weather in Ethnic Minority Areas in Southwest China. Int. J. Environ. Res. Public Health *16*, 2190. https://doi.org/10.3390/IJERPH16122190.

136. Ioannou, L.G., Testa, D.J., Tsoutsoubi, L., Mantzios, K., Gkikas, G., Agaliotis, G., Nybo, L., Babar, Z., and Flouris, A.D. (2023). Migrants from Low-Income Countries have Higher Heat-Health Risk Profiles Compared to Native Workers in Agriculture. J. Immigr. Minor. Health *25*, 816–823. https://doi.org/10.1007/S10903-023-01493-2/FIGURES/2.

137. Turek-Hankins, L.L., Coughlan de Perez, E., Scarpa, G., Ruiz-Diaz, R., Schwerdtle, P.N., Joe, E.T., Galappaththi, E.K., French, E.M., Austin, S.E., Singh, C., et al. (2021). Climate change adaptation to extreme heat: a global systematic review of implemented action. Oxford Open Climate Change *1*, 5. https://doi.org/10.1093/OXFCLM/KGAB005.

138. Zander, K.K., Cadag, J.R., Escarcha, J., and Garnett, S.T. (2018). Perceived heat stress increases with population density in urban Philippines. Environ. Res. Lett. *13*, 084009. https://doi.org/10.1088/1748-9326/AAD2E5.

139. Zhai, S.y., Song, G.x., Qin, Y.c., Ye, X.y., Leipnik, M., and Leipnik, M. (2018). Climate change and Chinese farmers: Perceptions and determinants of adaptive strategies. J. Integr. Agric. *17*, 949–963. https://doi.org/10.1016/S2095-3119(17)61753-2.

140. Habiba, U., Shaw, R., and Takeuchi, Y. (2012). Farmer's perception and adaptation practices to cope with drought: Perspectives from Northwestern Bangladesh. Int. J. Disaster Risk Reduct. *1*, 72–84. https://doi.org/10.1016/J.IJDRR.2012.05.004.

141. Wolff, N.H., Masuda, Y.J., Meijaard, E., Wells, J.A., and Game, E.T. (2018). Impacts of tropical deforestation on temperature and human well-being perceptions. Glob. Environ. Change *52*, 181–189.

142. Morrison, T.H., Adger, W.N., Agrawal, A., Brown, K., Hornsey, M.J., Hughes, T.P., Jain, M., Lemos, M.C., McHugh, L.H., O'Neill, S., and Van Berkel, D. (2022). Radical interventions for climate-impacted systems. Nat. Clim. Chang. *12*, 1100–1106. https://doi.org/10.1038/s41558-022-01542-y.

143. Nguyen, T.P.L., and Sean, C. (2021). Do climate uncertainties trigger farmers' out-migration in the Lower Mekong Region? Current Research in Environmental Sustainability *3*, 100087. https://doi.org/10.1016/J.CRSUST.2021.100087.

144. Mueller, V., Gray, C., and Kosec, K. (2014). Heat stress increases long-term human migration in rural Pakistan. Nat. Clim. Chang. *4*, 182–185. https://doi.org/10.1038/nclimate2103.

145. Gray, C., and Mueller, V. (2012). Drought and Population Mobility in Rural Ethiopia. World Dev. *40*, 134–145. https://doi.org/10.1016/J.WORLDDEV.2011.05.023.

146. Dun, O., McMichael, C., McNamara, K., and Farbotko, C. (2020). Investing in Home: Development Outcomes and Climate Change Adaptation for Seasonal Workers Living between Solomon Islands and Australia. Migration and Development *11*, 852–875. https://doi.org/10.1080/21632324.2020.1837535.

147. Chazalnoël, M.T., Mach, E., Ionesco, D., Kjellstrom, T., Lemke, B., Otto, M., Briggs, D., Zander, K., Goodman, J., and Fiske, L. (2017). Extreme Heat and Migration.

148. Liu, T., Xu, Y.J., Zhang, Y.H., Yan, Q.H., Song, X.L., Xie, H.Y., Luo, Y., Rutherford, S., Chu, C., Lin, H.L., and Ma, W.J. (2013). Associations between risk perception, spontaneous adaptation behavior to heat waves and heatstroke in Guangdong province, China. BMC Publ. Health *13*, 913. https://doi.org/10.1186/1471-2458-13-913/TABLES/7.

149. Oppermann, E., Strengers, Y., Maller, C., Rickards, L., and Brearley, M. (2018). Beyond Threshold Approaches to Extreme Heat: Repositioning Adaptation as Everyday Practice. Weather Clim. Soc. *10*, 885–898. https://doi.org/10.1175/WCAS-D-17-0084.1.

150. Schipper, E.L.F. (2020). Maladaptation: When Adaptation to Climate Change Goes Very Wrong. One Earth *3*, 409–414. https://doi.org/10.1016/J.ONEEAR.2020.09.014.

151. Hanmer, L.C., Klugman, J., Morton, M.H., and Singer, D. (2014). Gender at Work: A Companion to the World Development Report on Jobs.

152. Ngigi, M.W., Mueller, U., and Birner, R. (2017). Gender Differences in Climate Change Adaptation Strategies and Participation in Group-based Approaches: An Intra-household Analysis From Rural Kenya. Ecol. Econ. *138*, 99–108. https://doi.org/10.1016/J.ECOLECON.2017.03.019.

153. Chepkoech, W., Mungai, N.W., Stöber, S., and Lotze-Campen, H. (2020). Understanding adaptive capacity of smallholder African indigenous vegetable farmers to climate change in Kenya. Clim. Risk Manag. *27*, 100204. https://doi.org/10.1016/J.CRM.2019.100204.

154. Fletschner, D., Deo, S., Mhoja, M., Fletschner, D., and Deo, S. (2022). Championing Women's Tenure Security (Land Tenure Security and Sustainable Development), pp. 81–100. https://doi.org/10.1007/978-3-030-81881-4_5.

155. Aterido, R., Beck, T., and Iacovone, L. (2013). Access to Finance in Sub-Saharan Africa: Is There a Gender Gap? World Dev. *47*, 102–120. https://doi.org/10.1016/J.WORLDDEV.2013.02.013.

156. Doss, C.R., Deere, C.D., Oduro, A.D., and Swaminathan, H. (2014). The Gender Asset and Wealth Gaps. Development (Basingstoke) *57*, 400–409. https://doi.org/10.1057/DEV.2015.10/METRICS.

157. Deere, C.D., and Doss, C.R. (2008). THE GENDER ASSET GAP: WHAT DO WE KNOW AND WHY DOES IT MATTER?*12*, pp. 1–50. https://doi.org/10.1080/13545700500508056.

158. Asfaw, A., Simane, B., Bantider, A., and Hassen, A. (2019). Determinants in the adoption of climate change adaptation strategies: evidence from rainfed-dependent smallholder farmers in north-central Ethiopia (Woleka sub-basin). Environ. Dev. Sustain. *21*, 2535–2565. https://doi.org/10.1007/S10668-018-0150-Y/TABLES/8.

159. Herwehe, L., and Scott, C.A. (2018). Drought adaptation and development: small-scale irrigated agriculture in northeast Brazil. Clim. Dev. *10*, 337–346. https://doi.org/10.1080/17565529.2017.1301862.

160. Jaja, J., Dawson, J., and Gaudet, J. (2017). Using Social Network Analysis to examine the role that institutional integration plays in community-based adaptive capacity to climate change in Caribbean small island communities. Local Environ. *22*, 424–442. https://doi.org/10.1080/13549839.2016.1213711.

161. Kangalawe, R.Y.M., and Lyimo, J.G. (2013). Climate change, adaptive strategies and rural livelihoods in semiarid Tanzania. Nat. Resour. *04*, 266–278. https://doi.org/10.4236/NR.2013.43034.

162. Tambo, J.A., and Abdoulaye, T. (2013). Smallholder farmers' perceptions of and adaptations to climate change in the Nigerian savanna. Reg. Environ. Change *13*, 375–388. https://doi.org/10.1007/S10113-012-0351-0/METRICS.

163. Berrang-Ford, L., Sietsma, A.J., Callaghan, M., Minx, J.C., Scheelbeek, P.F.D., Haddaway, N.R., Haines, A., and Dangour, A.D. (2021). Systematic mapping of global research on climate and health: a machine learning review. Lancet. Planet. Health *5*, e514–e525. https://doi.org/10.1016/S2542-5196(21)00179-0.

164. Takakura, J., Fujimori, S., Takahashi, K., Hasegawa, T., Honda, Y., Hanasaki, N., Hijioka, Y., and Masui, T. (2018). Limited Role of Working Time Shift in Offsetting the Increasing Occupational-Health Cost of Heat Exposure. Earth's Future *6*, 1588–1602. https://doi.org/10.1029/2018EF000883.

165. Furoc-Paelmo, R., Cosico, R.S., Cabahug, R.E., Castillo, A.K., Castillo, A., and Visco, R. (2018). Farmers' Perception on the Sustainability of a Rubber- Based Agroforestry System as a Climate Change Adaptation Strategy in Agusan Del Sur and North Cotabato, Philippines. Journal of Environmental Science and Management *21*, 45–60. https://doi.org/10.47125/JESAM/2018_1/05.

166. Fernández de Velasco, G., Leppert, G., Moull, K., Prowse, M., Puri, J., Reumann, A., and Sánchez Torrente, L. (2021). Access to Credit as a Determinant of Autonomous Adaptation to Climate Change: A Meta-Analysis of the Evidence in Low- and Middle-Income Countries (DEU).

167. Castro, B., and Kuntz, C. (2022). Land Tenure Insecurity and Climate Adaptation: Socio-Environmental Realities in Colombia and Implications for Integrated Environmental Rights and Participatory Policy (Land Tenure Security and Sustainable Development), pp. 177–199. https://doi.org/10.1007/978-3-030-81881-4_9.

168. Branca, G., Lipper, L., Neves, B., Lopa, D., and Mwanyoka, I. (2011). Payments for Watershed Services Supporting Sustainable Agricultural Development in Tanzania. J. Environ. Dev. *20*, 278–302. https://doi.org/10.1177/1070496511415645.

169. Gbetibouo, G.A., Hassan, R.M., and Ringler, C. (2010). Modelling farmers' adaptation strategies for climate change and variability: The case of the Limpopo Basin, South Africa. Agrekon *49*, 217–234. https://doi.org/10.1080/03031853.2010.491294.

170. Antwi-Agyei, P., Dougill, A.J., and Stringer, L.C. (2014). Barriers to climate change adaptation: evidence from northeast Ghana in the context of a systematic literature review. Clim. Dev. *7*, 297–309. https://doi.org/10.1080/17565529.2014.951013.

171. Bormann, H., Van Der Krogt, R., Adriaanse, L., Ahlhorn, F., Akkermans, R., Andersson-Sköld, Y., Gerrard, C., Houtekamer, N., De Lange, G., Norrby, A., et al. (2015). Climate change adaptation through grassroots responses: learning from the "Aila" affected coastal settlement of

Please cite this article in press as: Masuda et al., Impacts of warming on outdoor worker well-being in the tropics and adaptation options, One Earth (2024), https://doi.org/10.1016/j.oneear.2024.02.001

Gabura, Bangladesh. Handbook of Climate Change Adaptation, pp. 2011–2034. https://doi.org/10.1007/978-3-642-38670-1_16.

172. Orlov, A., Sillmann, J., Aunan, K., Kjellstrom, T., and Aaheim, A. (2020). Economic costs of heat-induced reductions in worker productivity due to global warming. Glob. Environ. Change *63*, 102087. https://doi.org/10.1016/J.GLOENVCHA.2020.102087.
173. Vogel, B., and Henstra, D. (2015). Studying local climate adaptation: A heuristic research framework for comparative policy analysis. Glob. Environ. Change *31*, 110–120. https://doi.org/10.1016/J.GLOENVCHA.2015.01.001.
174. Lindegaard, L.S., and Sen, L.T.H. (2022). Everyday Adaptation, Interrupted Agency and beyond: Examining the Interplay between Formal and Everyday Climate Change Adaptations (Ecology and Society). https://doi.org/10.5751/ES-13610-270442.
175. Garg, T., Jagnani, M., and Taraz, V. (2020). Temperature and Human Capital in India. J Assoc Environ Resour Econ *7*, 1113–1150.
176. Lundgren, K., Kuklane, K., Gao, C., and Holmér, I. (2013). Effects of Heat Stress on Working Populations when Facing Climate Change. Ind. Health *51*, 3–15. https://doi.org/10.2486/indhealth.2012-0089.
177. Nunfam, V.F., Adusei-Asante, K., Van Etten, E.J., Oosthuizen, J., Adams, S., and Frimpong, K. (2019). The nexus between social impacts and adaptation strategies of workers to occupational heat stress: a conceptual framework. Int. J. Biometeorol. *63*, 1693–1706. https://doi.org/10.1007/S00484-019-01775-1/METRICS.
178. Hess, J.J., Errett, N.A., McGregor, G., Busch Isaksen, T., Wettstein, Z.S., Wheat, S.K., and Ebi, K.L. (2023). Public Health Preparedness for Extreme Heat Events*44*, pp. 301–321. https://doi.org/10.1146/ANNUREV-PUBLHEALTH-071421-025508.
179. International Labour Organization (2022). A Safe and Healthy Working Environment Is a Fundamental Principle and Right at Work.
180. Fanzo, J., Haddad, L., Schneider, K.R., Béné, C., Covic, N.M., Guarin, A., Herforth, A.W., Herrero, M., Sumaila, U.R., Aburto, N.J., et al. (2021). Viewpoint: Rigorous monitoring is necessary to guide food system transformation in the countdown to the 2030 global goals. Food Pol. *104*, 102163. https://doi.org/10.1016/J.FOODPOL.2021.102163.
181. Nolte, K. (2014). Large-scale agricultural investments under poor land governance in Zambia. Land Use Pol. *38*, 698–706. https://doi.org/10.1016/J.LANDUSEPOL.2014.01.014.
182. Liao, C., Nolte, K., Sullivan, J.A., Brown, D.G., Lay, J., Althoff, C., and Agrawal, A. (2021). Carbon emissions from the global land rush and potential mitigation. Nat. Food *2*, 15–18. https://doi.org/10.1038/s43016-020-00215-3.
183. Agrawal, A., Brown, D.G., and Sullivan, J.A. (2019). Are Global Land Grabs Ticking Socio-environmental Bombs or Just Inefficient Investments? One Earth *1*, 159–162. https://doi.org/10.1016/J.ONEEAR.2019.10.004.
184. Liao, C., Nolte, K., Brown, D.G., Lay, J., and Agrawal, A. (2023). The carbon cost of agricultural production in the global land rush. Glob. Environ. Change *80*, 102679. https://doi.org/10.1016/J.GLOENVCHA.2023.102679.
185. Davis, K.F., Yu, K., Rulli, M.C., Pichdara, L., and D'Odorico, P. (2015). Accelerated deforestation driven by large-scale land acquisitions in Cambodia. Nat. Geosci. *8*, 772–775. https://doi.org/10.1038/ngeo2540.
186. Davis, K.F., Koo, H.I., Dell'Angelo, J., D'Odorico, P., Estes, L., Kehoe, L.J., Kharratzadeh, M., Kuemmerle, T., Machava, D., Pais, A.d.J.R., et al. (2020). Tropical forest loss enhanced by large-scale land acquisitions. Nat. Geosci. *13*, 482–488. https://doi.org/10.1038/s41561-020-0592-3.
187. Chen, B., Kennedy, C.M., and Xu, B. (2019). Effective moratoria on land acquisitions reduce tropical deforestation: evidence from Indonesia. Environ. Res. Lett. *14*, 044009. https://doi.org/10.1088/1748-9326/AB051E.
188. Keith, L., and Meerow, S. (2022). Planning for Urban Heat Resilience. PAS Report 600.
189. Turner, J.A., Franklin, G., Fulton-Kehoe, D., Sheppard, L., Stover, B., Wu, R., Gluck, J.V., and Wickizer, T.M. (2008). ISSLS Prize Winner: Early Predictors of Chronic Work Disability. Spine *33*, 2809–2818. https://doi.org/10.1097/BRS.0B013E31817DF7A7.
190. Shameem, M.I.M., Momtaz, S., and Kiem, A.S. (2015). Local perceptions of and adaptation to climate variability and change: the case of shrimp farming communities in the coastal region of Bangladesh. Clim. Change *133*, 253–266. https://doi.org/10.1007/S10584-015-1470-7/METRICS.
191. Singh, C., Daron, J., Bazaz, A., Ziervogel, G., Spear, D., Krishnaswamy, J., Zaroug, M., and Kituyi, E. (2018). The utility of weather and climate information for adaptation decision-making: current uses and future prospects in Africa and India. Clim. Dev. *10*, 389–405. https://doi.org/10.1080/17565529.2017.1318744.
192. Jones, L., Dougill, A., Jones, R.G., Steynor, A., Watkiss, P., Kane, C., Koelle, B., Moufouma-Okia, W., Padgham, J., Ranger, N., et al. (2015). Ensuring climate information guides long-term development. Nat. Clim. Chang. *5*, 812–814. https://doi.org/10.1038/nclimate2701.
193. Adger, W.N., Dessai, S., Goulden, M., Hulme, M., Lorenzoni, I., Nelson, D.R., Naess, L.O., Wolf, J., and Wreford, A. (2009). Are there social limits to adaptation to climate change? Clim. Change *93*, 335–354. https://doi.org/10.1007/S10584-008-9520-Z/METRICS.
194. Rosenthal, N., Benmarhnia, T., Ahmadov, R., James, E., and Marlier, M.E. (2022). Population co-exposure to extreme heat and wildfire smoke pollution in California during 2020. Environ. Res, Climate *1*, 025004. https://doi.org/10.1088/2752-5295/AC860E.
195. Reckien, D., Magnan, A.K., Singh, C., Lukas-Sithole, M., Orlove, B., Schipper, E.L.F., and Coughlan de Perez, E. (2023). Navigating the continuum between adaptation and maladaptation. Nat. Clim. Chang. *13*, 907–918. https://doi.org/10.1038/s41558-023-01774-6.
196. Intergovernmental Panel on Climate Change (IPCC) (2023). In Climate Change 2022 – Impacts, Adaptation and Vulnerability H, O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, and V. Möller, et al., eds. (Cambridge University Press). https://doi.org/10.1017/9781009325844.
197. Magnan, A.K., Schipper, E.L.F., Burkett, M., Bharwani, S., Burton, I., Eriksen, S., Gemenne, F., Schaar, J., and Ziervogel, G. (2016). Addressing the risk of maladaptation to climate change*7* (Wiley Interdiscip Rev Clim Change), pp. 646–665. https://doi.org/10.1002/WCC.409.
198. Juhola, S., Glaas, E., Linnér, B.O., and Neset, T.S. (2016). Redefining maladaptation. Environ. Sci. Policy *55*, 135–140. https://doi.org/10.1016/J.ENVSCI.2015.09.014.
199. Colelli, F.P., Wing, I.S., and Cian, E.D. (2023). Air-conditioning adoption and electricity demand highlight climate change mitigation–adaptation tradeoffs. Sci. Rep. *13*. 4413-12. https://doi.org/10.1038/s41598-023-31469-z.
200. Mastrucci, A., Byers, E., Pachauri, S., Rao, N., and van Ruijven, B. (2022). Cooling access and energy requirements for adaptation to heat stress in megacities. Mitig. Adapt. Strateg. Glob. Chang. *27*. 59-16. https://doi.org/10.1007/S11027-022-10032-7/FIGURES/3.
201. Goodwin, S., Olazabal, M., Castro, A.J., and Pascual, U. (2023). Global mapping of urban nature-based solutions for climate change adaptation. Nat. Sustain. *6*, 458–469. https://doi.org/10.1038/s41893-022-01036-x.
202. Turner, B., Devisscher, T., Chabaneix, N., Woroniecki, S., Messier, C., and Seddon, N. (2022). The Role of Nature-Based Solutions in Supporting Social-Ecological Resilience for Climate Change Adaptation*47*, pp. 123–148. https://doi.org/10.1146/ANNUREV-ENVIRON-012220-010017.
203. USAID Administrator Samantha Power Launches the Prepare Call to Action to the Private Sector. Preprint.
204. IPCC (2023). Urgent Climate Action Can Secure a Liveable Future for All. Preprint.
205. World Resources Institute (2023). Adaptation Action Coalition (World Resources Institute). https://www.wri.org/initiatives/adaptation-action-coalition.
206. Morris, N.B., Jay, O., Flouris, A.D., Casanueva, A., Gao, C., Foster, J., Havenith, G., and Nybo, L. (2020). Sustainable solutions to mitigate occupational heat strain - An umbrella review of physiological effects and global health perspectives. Environ. Health *19*. 95-24. https://doi.org/10.1186/S12940-020-00641-7/TABLES/3.
207. Peckham, T.K., Baker, M.G., Camp, J.E., Kaufman, J.D., and Seixas, N.S. (2017). Creating a Future for Occupational Health. Ann. Occup. Hyg. *61*, 3–15. https://doi.org/10.1093/annweh/wxw011.