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TITLE. Occupational heat stress and related social and economic losses: a scoping literature review.

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Introduction

There is a consistent body of evidence that high outdoor and indoor temperatures have adverse health effects in exposed workers (1). Workers are normally healthier than the general population, but they, especially those severely exposed and engaged in heavy workloads, may be equally affected by heat stress when the thermoregulatory capacity of the body is overcome, activating physiological pathways resulting in heat-related illness, acute outcomes (e.g. myocardial infarction) or exacerbations of pre-existing diseases (e.g. cardiovascular and respiratory outcomes) (2). Individuals working in the heat are also prone to physical strength losses and cognitive function impairments, leading to work-related injuries (3), missed workdays and productivity reductions (4) and, in the long term, may develop chronic kidney impairment (5,6). Health and productivity outcomes related to heat strain have a huge impact in terms of social and economic costs on the different actors involved: the workers themselves due to the temporary or permanent health and quality of life impairments and missed wages, the farm or factory due to necessity of maintaining production despite employees absences or output reductions, the healthcare system due to the healthcare expenditures due to workers seeking care, the social security or insurance system due to reimbursements to labourers for injuries, permanent disability or occupational diseases, and the whole country or region in terms of reductions of the Gross Domestic Product due to production losses in specific economic sectors. Moreover, climate change is expected to worsen heat exposure in some regions exceeding work-related productivity thresholds (7).

Heat exposure in the workplace is a growing hazard throughout the world, considering climate change scenarios showing a universal increase in heat extremes virtually in every region, but larger in Central and South America, in the Mediterranean region, north Africa, the Arabian peninsula, India and South-east Asia (8). Most of the affected regions are low-income economies mostly relying on manual labor and manufacturing work with agriculture, construction being the economic sectors at higher risk of heat exposure and at higher workload intensity than others. The quantification of economic impacts of heat exposure in the workplace are of worth for individual companies, labour policy makers, insurance companies, but also for occupational safety and healthcare systems and should be taken into account when analysing markets and economies at local and global scale. The knowledge of economic losses related to heat may serve as a basis to plan adjustment measures at company level, or to set up specific heat adaptation policies or to strengthen social security systems by enclosing climate risk concerns, especially towards poorer population and countries (9).

Differently from the strong evidence available on the effects of heat on workers' health and safety, there is still limited but growing evidence about the resulting social and economic impacts (10–12). This is complicated by the lack of a gold standard both in methods used for evaluation (i.e. epidemiological versus econometric studies), both in operational definitions of productivity losses (e.g. lost worktime, reported physical and cognitive performance reductions, work output reductions in case of manual workers), heat-productivity functions (e.g. work breaks needed based on Wet Bulb Globe Temperature threshold exceedance) and economic costs (i.e. lost salaries and wages due to fatigue/sickness, cost per compensable claim, healthcare costs related to treatment and rehabilitation).

A comprehensive literature review was carried out to update knowledge about social and economic impacts related to workplace heat exposure, by considering the whole body of evidence deriving from both epidemiological studies, econometric models and hybrid approaches to inform relevant stakeholders in the field.

Methods

Literature search has been conducted in two bibliographic databases (Web of Science and Pubmed), up to April 2022, using both free terms and controlled vocabulary (**Appendix 1**) to select studies on which evaluated productivity (e.g. work hours), economic (i.e. monetary costs) or social impacts (e.g. work absences) of occupational heat exposure (both indoor and outdoor) on workers. The first group of relevant studies were epidemiological studies (both qualitative and quantitative) on workers estimating productivity losses in the field or estimating costs related to occupational heat-related illnesses (e.g. injuries). The second category of suitable studies were the recent piece of literature of economic studies adopting a mix of approaches (e.g. structural economic models, econometric models) estimating impacts of climate change on labour productivity and related economic costs using occupational health and safety recommendations in an entire economic sector and for regional or global economies. All occupational sectors were on interest since both indoor and outdoor heat exposure was considered. Laboratory studies (e.g. on physiological responses), epidemiological studies on occupational heat-related illnesses not estimating their economic implications, studies focusing only on cognitive function of workers related to heat, studies on other occupational exposures (e.g. cold, air pollution) were excluded. Only original studies were retrieved, while literature reviews were excluded but used to screen for additional relevant studies. The selection of studies and data extraction were conducted according to PRISMA guidelines (13). The outcomes considered were:

- Lost productivity estimated or perceived by the worker associated with the heat exposure;
- Economic costs associated with heat-related injuries or hospitalizations in workers;
- Projections of economic costs related to productivity losses due to heat under climate change.

Given the heterogeneity of study designs, methods for estimating costs or productivity, outcomes considered and occupational sectors investigated, a narrative synthesis was undertaken by grouping studies by design (epidemiological vs economic studies). Published reviews on the topic (10–12,14–16), the 6th assessment report of the Intergovernmental Panel on Climate Change (https://www.ipcc.ch/report/ar6/wg2/) were also screened to avoid to exclude relevant publications in the field.

Results

A total of 8153 potentially relevant records were identified after duplicates were removed, of which 103 identified from previous reviews on the topic (**Appendix 2**). Out of these, 138 were assessed as full text because potentially relevant and finally 90 studies were included in the qualitative synthesis.

Results from epidemiological studies

Table 1 describe results of the epidemiological studies (n=39), including 31 field studies and 8 studies estimating healthcare-related costs.

Field studies

Most field studies (20 out of 31) were conducted in low or middle income countries (17,18,27–36,19–26), with only 10 studies from Europe, USA and Australia/New Zealand ((37–46) and one multicentric study (47). Studies adopted questionnaires or interviews on around 1-3 hundreds workers (the study size overall ranging from16 (24) to 4095 workers (19) in different occupational sectors (9 on agriculture, 4 on construction, 1 on mining and 17 from several sectors) also including indoor workers (12 studies). Three studies were qualitative based on interviews or focus groups (27,40,44), while the other studies were quantitative with 26 cross-sectional and 2 longitudinal (repeated surveys) studies (36,39), and provided an estimation of the association between heat and labour productivity estimated or perceived by workers.

Despite the large heterogeneity in the work sectors and study size, all field studies, except one (39), consistently showed a reduction in productivity due to occupational heat exposure. The estimated productivity losses ranged between 0.3% to 10% reduction for an increase of 1°C in temperature (24,31,34,36). Other studies quantified productivity losses as lost worktime expressed in absolute or percentage terms (20,24,29,34,35,45), or as reduction in daily output in absolute or percentage terms (19,22,31–33). Four studies (Zander 2015, Zander and Mathew, 2019, Morabito 2020, Vanos 2019) also provided an estimate of the related economic costs by applying the productivity losses to the gross wages of workers. The study by Langkulsen et al. (22) showed a reduction in productivity only in two of the occupational sectors considered (pottery and construction), but not in the others. Perhaps the lack of association in the study of Lamb et al. (39)

could be explained by the fact there was evaluated a thermal stress variable including both heat and cold temperature, therefore their single contributions on work performance could not be disentangled. Given the cross-sectional approach adopted in most studies, the results do not allow causal inference on the association between occupational heat exposure and work productivity.

In some field studies specific workers subgroups appeared to be more susceptible to the productivity losses due to occupational heat exposure: men (28,32,46), younger, less educated or less experienced workers (28), workers exposed to direct sun (47), workers performing heavy tasks (32,46), those using personal protective equipment (PPE) such as masks (23,37,41), those affected by comorbidities such as kidney failure or other conditions (19,20), immigrant workers (42), workers not following safety protocols such as hydrating, taking breaks in cooling places (18,28).

Healthcare-related studies

In contrast to field studies, the 8 studies estimating healthcare-related costs due to occupational heat exposure used data from administrative databases, therefore they were mostly conducted in western countries such as Europe, Australia, the US and Canada (48–54), with only one study from China (55). Six studies evaluated workers from all occupational sectors, while three studies evaluated specific occupational sectors such as agriculture and construction. Four studies were descriptive analysis of occupational injuries or diseases identified as heat-related and consequent compensation costs in specific occupational sectors (48–51), while the other four were etiological studies estimating the occupational injuries attributable to heat exposure through time-series or case-crossover analysis and then quantifying the related costs (52–55).

The national Spanish study from Martinez-Solanas et al. (52) was the only one to estimate heat-related injuries related costs including not only the social or private insurance refund to the workers (for long-term losses) or to the healthcare system, but also costs due to the factory for production maintenance, and those associated with workers pain and suffering. The total economic impact of heat-related injuries in the study period was 370 million euros, equal to 0.03% of Spain’s GDP with the costs associated with pain and suffering were higher than other types of costs. The Chinese study of Ma et al. (55) evaluated the attributable fraction of insurance payout related to occupational heat exposure (temperatures above the limit of the wet bulb globe temperature (WBGT) in accordance with international standards) as 4.1% (95%CI 0.2%-7.7%). The South-Australian study on construction industry (53) compared the costs associated with accidents on heat wave days to control days, highlighting in particular higher injuries costs in the urban area than in the suburbs and in relation to specific agents of injury (i.e.work platform, electricity and equipment). In the other south-Australian study (54), an increase in maximum temperature above

33°C was associated with an increase of 41.6% in health costs and 74.8% in working days lost due to heat-related injuries.

Two US studies (49,50) were conducted on the same area in different periods, allowing for a temporal comparison. The median cost per heat-related injury was higher in the second period $909 in 2006-2017 compared to $537 in 1995-2005 and also the average worktime loss for time loss claims was higher in the latter period (93 days per claim vs 46 days per claim in the first) and the median accident temperature increased from 85°F to 90°F. Another US study (48) estimated a median cost per claim of $654 similar to the Bonauto et al. study (49) and higher costs related with non-compensable claims, in particular in the agriculture and forestry sector, suggesting a possible under-reporting of work related accidents in this sector. A Canadian study (51) used as a measure of social costs of heat-related effects on workers the rate of lost time injuries since these are related to time off work or productivity losses was 1.7 cases per million months of permanent employment).

Studies estimating healthcare-related costs suggest some workers subgroups are related to higher costs or work time losses such as manual workers (51), black workers and Latinos (50), workers employed for less than two months (51), workers aged 15-24 years (51), women (55), workers of small (53) or medium-sized companies (54,55).

<u>Results from economic studies</u>

Table 2 describe results of the economic studies (n=51). Studies based on economic models have used different approaches to estimate the economic costs associated with heat-associated reductions in worker productivity. The simplest method starts from the productivity losses estimates based on occupational health and safety standards of the different employment sectors and multiplies it by the share to which each labour sector contributes to GDP. Most included studies estimated productivity as a function of the ISO 7243 standard on the risk associated with thermal stress by considering exceeding a threshold of the wet bulb globe temperature indicator (WBGT) at the workplace or on the basis of the standard of thermal comfort, the Predicted Mean Vote Index, and associate climate data with economic data. This method does not consider the relationships and influence between economic sectors, an aspect taken into account by the more complex structural economic models based on the so-called computable general equilibrium (CGE) model or general equilibrium models. General equilibrium models are a class of economic models that use actual economic data to estimate how an economy might react to changes in policy, technology or other external factors. In most cases, the impact of climate change in 2030, 2050 and 2080 was estimated by considering low and high greenhouse gas (no mitigation) scenarios at global and regional level. Other studies have assessed the impact in specific regions, and others have considered the economic impacts of the current climate.

Global studies

Studies evaluating global economic impacts of occupational heat (n=21) were both scientific publications (56,57,66–70,58–65) and grey reports (71–74) and one online dashboard later published (75). Productivity losses associated with climate change by 2100 globally range from 1% (71) to 47% (64) under the worst-case scenario (no mitigation). In specific sectors such as agriculture and in specific countries the loss of productivity expressed as a percentage reduction in GDP is even greater than 30-50% (59,63,66) in particular the highest productivity losses are associated with workers who perform more intense physical activities (400W) outdoors (63).

Regional studies

Also regional studies (n=30) included both published (23,76,85–94,77,95,78–84) and grey literature (96–104). At the regional level, studies show that tropical regions such as West Africa, Southeast Asia, Central and South America are the most affected. Even the southern Mediterranean regions such as Italy have an expected impact that is not negligible, greater than the northern regions of Europe. Agriculture is the most affected sector of thermal stress due to the heat both considering the current climate and future scenarios.

Discussion

The literature review provides an updated summary of the evidence about economic impacts of occupational heat exposure. Throughout the different study types, ranging from epidemiology to economics, it emerges a clear picture of the social and economic impacts of heat exposure in the workplace, although the most consistent evidence shows impacts at region or country Gross Domestic Product, especially in countries where there is a larger manual working population and where climate change scenarios predict the steeper rise in temperatures. Productivity losses associated with climate change by 2100 globally range from 1% (71) to 47% (64) under the worst-case scenario (no mitigation). In specific sectors such as agriculture and in specific countries the loss of productivity expressed as a percentage reduction in GDP is even greater than 30-50% (59,63,66). Epidemiological evidence, especially about the economic costs related to occupational injuries and disease is still poor and need to be reinforced in next years. Interestingly the Spanish study of Martinez-Solanas et al. on heat-related injuries (52) was able to estimate not only the costs related to social or private insurance refund to the workers (for long-term losses) or to the healthcare system, but also costs due to the factory for production maintenance, and those associated with workers pain and suffering, with the latter accounting for a higher rate than other costs. Overall, our findings confirms the results of previous reviews (10–12,14–16) and of the latest IPCC report (7) adding further evidence to the association between hot exposure (indoor and outdoor) and loss of productivity or costs for the workers and the farm or factory.

Overall, epidemiological studies have the added value to provide some insights into the workers categories most vulnerable to productivity losses or economic consequences of injuries. These groups included: manual workers (51), black workers and Latinos (50), workers of small (53) or medium-sized companies (54,55), men (28,32,46), younger, less educated or less experienced workers (28,51), workers exposed to direct sun (47), workers performing heavy tasks (32,46), those using personal protective equipment (PPE) such as masks (23,37,41), those affected by comorbidities such as kidney failure or other conditions (19,20), immigrant workers (42), workers not following safety protocols such as hydrating, taking breaks in cooling places (18,28). In these subgroups it can be assumed that the heat-related injuries were more serious due to heavier tasks or because they are less aware of the risks and prevention strategies, and larger attention is needed in terms of prevention. This can be particularly challenging especially in small businesses which seem to be more prone to more severe accidents but which on the other hand require less resources compared to large companies to improve prevention and protection in the workplace.

Some occupational sectors seem more affected than others, primarily agriculture, construction suggesting on one hand a higher impact on productivity and higher risk of injuries in workers who perform more intense physical activities (400W) outdoors, but some studies suggested a possible under-reporting of work related accidents especially in the agriculture sector (49). There is also some evidence that for healthcare workers, the risk of occupational heat stress grew during the COVID-19 pandemic due to the need to wear personal protective equipment (37,41).

Despite the large heterogeneity in terms of methodologies used, heat exposure indicators, economic cost measures did not allow a quantitative synthesis, the review provides a clear indication of the consistency of the effects of heat on productivity and costs for workers, a useful indication for decision-making. The European Commission has already taken a number of initiatives in this field. The evidence available suggests that the expected impacts of climate change may be even greater, which is why it is necessary to reinforce the dissemination of information and prevention and safety in the workplace at global level, particularly in low and middle income countries.

Conflicts of Interest

None

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Table 1. Results of epidemiological studies estimating productivity, social or economic losses related to occupational heat exposure.

Reference	**Study type**	**Country**	**Heat exposure**	**Study population**	**Study period and duration**	**Cost calculation**	**Economic loss estimation (unit measure)**	**Results**
Amini 2021	field study	southwest Iran	predicted mean vote (PMV) index	agriculture workers	2016	Productivity calculated based on equation in Mohamed 2005 doi: 10.1016/j.ergon.2004.09.008.	Manpower productivity index	A strong and significant ($P < 0.05$) relationship between temperature index in the cold regions was found. In the hot regions, all three main environmental variables have a strong and significant correlation ($P < 0.05$) with the P index.
Budhathoki, N. K. 2019	field study	Nepal	Perceived stress from heat and heat waves	350 farmers	2012-2017	na	perceived labour productivity due to heat	Farmers' perceived heat stress levels, and the number of associated illnesses or symptoms, significantly increase labour productivity loss during heat waves ($p < 0.05$). Residency in urban areas, access to weather information, past implementation of prevention measure increases labour productivity losses perception due to heat.
Dally 2018	field study	Guatemala	Wet-bulb Globe Temperature (WBGT) index of heat stress	4,095 sugarcane cutters	November 2015 to May 2016 harvest season.	distributed lag non-linear models were used to model the relationship between temperature exposure and productivity (lag 0-5)	change in average daily tons	The cumulative effect on tons of sugarcane cut for workers with impaired kidney function who experienced exposure to a WBGT of 34°C is estimated to be a loss of 1.16 (95% confidence interval (CI): -2.87, 0.54) tons over the next five days compared to if they were exposed to a WBGT of 29°C. The estimated cumulative effect on tons of sugarcane cut by workers with functioning kidneys was 0.59 tons (95% CI: -2.05, 0.87) less.
Das 2015	field study	India (two cities)	heat wave days	150 low-income urban informal workers (mostly outdoor)	April-May 2013	survey and analysis of Change in time allocation and work time loss as a function of workplace, family size and income, and worker's health during heat wave compared to normal days	Lost worktime (in hours)	The results show that workers work 1.19 h less and spend 0.46 h less at home, and they rest 1.65 h longer on average on a heat wave day than on a normal summer day. Work time loss is more for people doing manual work and having health problems
Davey 2021	field study	UK	perceived heat stress and heat-related illness	healthcare workers	May and August 2020	difficulty in performing specific work procedures	reported cognitive and physical performance	heat stress impaired both cognitive and physical performance of workers. respondents reported that PPE impaired their physical performance at work (76%) and made their job more difficult (92%)
Delgado-Cortez (2009)	field study	Nicaragua	Wet-bulb Globe Temperature (WBGT) index of heat stress	22 sugarcane workers	2006/2007 harvesting season (15 days)	field study and descriptive analysis of production output and water intake (no analysis of production output and temperature)	daily productivity output (in tons)	Output production increased significantly among those best hydrated, from 5.5 to 8 tons of cut sugarcane per worker per day.
Gun & Budd 1995	field study	Australia	Wet-bulb Globe Temperature (WBGT) index of heat stress	43 male sheep shearers	January-March of two consecutive years (54 days)	linear regression analysis between productivity and thermal stress variables	Shearers and press operators were paid by the hourly number of sheep shorn and wool bales pressed, respectively, which were recorded in a tally book maintained by the employing contractor; these records thus provide an accurate measure of productivity. Because of the dissimilarity of the units (sheep vs. bales), tallies reported in this paper are those of the shearers only	Slowing down because of discomfort is suggested by the finding that uncomfortably warm shearers tended to be less productive (r = - 0·32, , b = - 3·0, p = 0·04), but this association might simply reflect the less skilled shearers' higher energy cost per sheep shorn (Poole and Ross 1983). Clearer evidence of a reduced work rate is provided by the retrospective study (figure 5),

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Cost calculation	Economic loss estimation (unit measure)	Results
Lamb 2016	field study	New Zealand	Indoor Environmental Quality (thermal stress including both cold and heat stress)	114 office workers	8 months	longitudinal within-subjects design	An 11-point scale measured work performance relative to perceived average work performance	Thermal comfort did not significantly affect work performance
Langkulsen et al. (2010)	field study	Thailand	Wet-bulb Globe Temperature (WBGT) index of heat stress	21 workers in pottery industry, power plant, knife industry, construction site and agricultural site	October 5 to October 16, 2009	cross-sectional study of perceived productivity loss due to heat stress	Productivity loss measured as percent change of the daily work output	In knife and agriculture workers no losses of productivity. In power plant workers not applicable. In pottery and construction workers losses of productivity up to 10% and 120% respectively.
Lao, 2016	field study	South Australia	na	32 male outdoor workers	July 2014	Focus groups on heat impact on work productivity	productivity self-evaluated in a narrative way by workers	Narratives revealed that working on hot days could affect health and well-being, and work productivity
Lee 2020	field study	India and Singapore	perceived heat stress	165 hospital workers using PPE during covid-19 epidemic	May-June 2020	cross-sectional study of perceived productivity loss due to heat stress and PPE	perceived productivity self-assessed from questionnaire	workers reported a reduced productivity due to heat and when wearing PPE
Li 2016	field study	China	Wet Bulb Globe Temperature	16 rebar workers	summer 2014	Three regression models were constructed that focused on direct work time, indirect work time, and idle time to analyze the impacts of the WBGT and other factors affecting labor productivity	labor productivity measurements of direct work time, indirect work time and idle time	high-temperature environments decrease labor productivity, with the percentage of direct work time decreasing by 0.57% and the percentage of idle time increasing by 0.74% when the WBGT increased by 1 °C. Moreover, the percentage of direct work time increased by 0.33% when the workers' experience increased by 1 year and decreased by 0.72% when the workers' age increased by 1 year.
Lundgren, 2014	field study	Chennai, India	Wet-bulb Globe Temperature (WBGT) index of heat stress	77 workers in industrial, service, and agricultural sectors (most workers with moderate to heavy work)	JanuaryFebruary and AprilMay	Cross-sectional study with Heat strain and associated impacts on labour productivity between the seasons were assessed using the International Standard ISO 7933:2004, which applies the Predicted Heat Strain (PHS) model. Productivity losses collected from questionnaire.	Productivity loss based on Predicted Heat Strain (PHS) model from core temperature and maximum water loss	Heat strain was related to productivity loss in the PHS model in all workplaces, apart from the laundry facility, especially during the hot season
Lundgren-Kownacki1 2018	field study	India	perceived heat stress	87 brick kiln workers in summer and 61 in winter	June–July 2013, March–April 2014 (hot season); February 2013, January–February 2015 (cool season)	Cross-sectional study with productivity measured by questionnaire	Absenteeism/taken sick leave due to heat; Less productivity/more time to complete task/work extra hours; Irritation/interpersonal issues; Wages lost	16% of workers in summer reported abseteeism/sick leave due to heat stress, 48% reported less productivity
Mathee 2010 - HOTHAPS study	field study (qualitative study)	South Africa	perceived heat stress	151 workers involved in sun-exposed occupations.	March 2009	no analysis was carried out, only narrative description of interviews	self-reported productivity loss	The study is part of the HOTHAPS study. Where daily maximum temperatures may reach 40°C, workers reported a wide range of heat-related effects, leading to difficulty in maintaining work levels and output during very hot weather

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Cost calculation	Economic loss estimation (unit measure)	Results
Messeri 2019 (EU HEAT-SHIELD project)	field study	Italy	perceived heat stress	104 migrant workers in agriculture and construction	summer months of 2017	Self-reported data (the worker noticed to be less productive during a heat wave or need more energy for the same work)	perceived productivity loss due to heat	migrant workers declared that work required greater effort than do native Italian workers (Chi squared p = 0.001) but reported less impact from heat on productivity (Chi squared p = 0.014) and thermal discomfort
Messeri 2021 (WORKLIMATE project)	field study	Italy	perceived heat stress	191 hospital workers using PPE during covid-19 epidemic most from Centre-South of Italy	June-October 2020	Cross-sectional study of perceived productivity loss due to heat stress and PPE. Descritptive analysis and Principal Component Analysis.	perceived productivity self-assessed from questionnaire	A great number of HCW (81%) self-reported a productivity loss related to heat stress exposure. The productivity loss (item 28) was found to be significantly correlated (p<0.001) to the perception of thermal sensation due to the use of PPE.
Morabito et al., 2020	field study	Florence and Guangzhou	Wet-bulb Globe Temperature (WBGT) index of heat stress	18 outdoor workers in agriculture	Summer 2017-2018	Cross-sectional study to assess productivity loss in outdoor workers for moderate (300 W) work activities in sun and shady areas. Exposure-response function of WGBT and productivity is assessed by using two risk functions: based on ISO standard and on epidemiological data (Kjellstrom et al., 2018)	Percent productivity loss (%) self-assessed from questionnaire and economic costs estimated from workers' salaries multiplied for productivity losses.	The hourly economic cost in italian farm related to the productivity loss in the sun during the typical working time ranged between €5.7 and €8.0, higher than productivity loss in the shade. The productivity loss values estimated in the sun in Guangzhou were 7.3, 8.2 and 8.3 times higher than the values estimated in Florence and even greater considering shade conditions.
Nunfam 2021	field study	Ghana	perceived heat stress	320 miners	October 2017-January 2018	Cross-sectional study to assess health and productivity related to heat	perceived productivity self-assessed from questionnaire	Heat exposure had a significant direct effect on the productivity outcomes of mining worker. Variability in productivity was explained by heat exposure, moderated by barriers to adaptation strategies,mediated through adaptation strategies and controlled by some demographic and work-related variables.
Pradhan 2013 - HOTHAPS study	field study	Nepal	Wet-bulb Globe Temperature (WBGT) and Humidex	120 workers indoor and outdoor	2010	descriptive comparison of work time across months	average work hours by season (work efficiency)	duration of work is longer in summer due to longer days and more frequent rests or longer mid-day off.
Quiller, 2017*	field study	Washington, US	Wet-bulb Globe Temperature (WBGT) index of heat stress	46 tree harvesters	2015 August and September	Cross-sectional study estimating the relationship between WBGT and productivity	productivity (total weight of fruit bins collected per time worked)	There was a trend of decreasing productivity with increasing WBGT, but this was not statistically significant (significant only in unadjusted model)
Sadiq 2019	field study	Nigeria	Wet-bulb Globe Temperature (WBGT) index of heat stress	396 maize farmers	July to September, 2016	multiple linear regression was used to determine the influence of temperature (WBGT), body mass index (BMI), age, and gender on the productivity of the farmers.	work output based on the number of ridges cultivated during the working hours	Productivity was significantly higher between the hours of 6–9 am ($p < 0.001$) and 12–3 pm ($p < 0.001$), compared to the hours of 9 am–12pm ($p < 0.001$)- For temperature increases, productivity decreases (beta coefficient = −0.6, p-value <0.001).
Sahu et al. (2013).	field study	India	Wet-bulb Globe Temperature (WBGT) index of heat stress	124 rice harvesters	April-June 2011	Cross-sectional study to assess health and productivity related to heat. Productivity estimated for WBGT exceeding the standard (26-32°C) corresponding to 30-38°C of air temperature	change of the hourly work output. Daily work output was measured in terms of volume or quantity of items collected	High heat exposure in agriculture caused heat strain and reduced work productivity (-5% per 1°C). This reduction will be exacerbated by climate change and may undermine the local economy
Sett, 2014*	field study	West Bengal, India	Wet-bulb Globe Temperature	120 female brickfield	October 2008 to May 2009 (first	Longitudinal study to assess health and productivity related to heat. Productivity estimated	throughout the 8-month working period, their productivity was recorded on a	Productivity loss for every degree rise in temperature was about 2%

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Cost calculation	Economic loss estimation (unit measure)	Results
			(WBGT) index of heat stress		session), from October 2009 to May 2010 (second session), and then from October 2010 to May 2011 (third session)	for WBGT exceeding the standard (26-32°C) corresponding to 30-38°C of air temperature	weekly basis from the record register book for three sessions, and it was calculated as productivity per person per week	
Singh 2013	field study (qualitative study)	Australia	n.a.	47 workers outdoor in several industries (encl. Farming, construction)	summer 2010	no analysis was carried out, only narrative description of interviews	self-reported productivity loss	All interviewees reported that excessive heat exposure presents a significant challenge for their industry or activity. People working in physically demanding jobs in temperatures>35°C frequently develop symptoms, and working beyond heat tolerance is common. To avoid potentially dangerous health impacts they must either slow down or change their work habits. Such health-preserving actions result in lost work capacity.
Vanos et al. 2019	field study	Ontario, Canada	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor laborers at an industrial worksite	2012 - 2018 (May-October)	Cross-sectional study to assess workers health and productivity related to heat stress	loss of money due to heat per 15-minute work interval by laborer type (via hourly wages)	On average, 22 hours per worker were lost each summer (ca 1% of annual work hours) as a result of taking breaks or stopping due to heat. This amount of time corresponded to an average individual loss of 1100 Canadian dollars to workers or the company
Venugopal et al. (2016)a	field study	South India	Wet-bulb Globe Temperature (WBGT) index of heat stress	84 steel workers	April 2014	cross-sectional study of perceived productivity loss due to heat stress	Productivity loss due to heat stress was defined as loss in production, not achieving work targets, loss of workdays/work hours due to fatigue/exhaustion, sickness/hospitalization, and/or wages lost due to heat or heat-related illnesses	Workers exposed directly to heat sources reported higher productivity losses than other workers. Heat exposure was related to greater absenteeism (+1% increase), less productivity (-10.6%), larger work extra hours (26.9%) and increase in irritation/interpersonal issues (+7.7%)
Venugopal et al. (2016)b	field study	India	Wet-bulb Globe Temperature (WBGT) index of heat stress	several occupation types (indoor and outdoor, heavy, moderate and light)	cooler (2012) and hotter (2013) seasons	Cross-sectional study to assess workers health and productivity related to heat and cold stress	Productivity loss due to heat stress was defined as loss in production, or not achieving set work targets, or loss workdays/work hours due to fatigue/exhaustion, or sickness/hospitalization, and/or wages lost due to heat or heat related illnesses.	Of the 442 workers, approximately 62% reported reduced productivity by not achieving targets, 30% reported absenteeism as a reason for productivity loss and 25% workers' reported lost wages due to fatigue/sickness due to workplace heat-stress. males and workers with heavy workload were significantly affected by heat-related productivity losses
Yi, 2017	field study	Hong-Kong	Wet-bulb Globe Temperature (WBGT) index of heat stress	14 male construction workers	August and September 2016	Cross-sectional study to assess workers health and productivity related to heat stress to built a model for predicting labor productivity loss	productive work activities (Make use of wrenches to connect, cut, band, and modify reinforcing steel bars, Place reinforcing steel bars, Modify reinforcing steel bars, Carry reinforcing steel bars, Use meter sticks for measurements, Bending), Non-Productive Activities (Employees or	The model revealed that heat stress reduces construction labor productivity, with the percentage of direct work time decreasing by 0.33% when the WBGT increased by 1 °C.

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Cost calculation	Economic loss estimation (unit measure)	Results
							machines, or both, due to work stoppage from any cause; Chat, smoke, drink, sit, use cell phones, go to the washroom)	
Zander et al. 2015	field study	Australia	self reported heat stress	1726 workers in several occupation types	2013/2014	self-reported estimates of work absenteeism and reductions in work performance caused by heat	Self-reported estimates of absenteeism and reductions in work performance (presenteeism) caused by heat	The individual economic losses due to heat were US$655 per person, which translates to an economic burden totaling US$6.2 billion in Australia
Zander and Mathew, 2019	field study	Urban Malaysia	self reported heat stress	514 workers several occupation types	2017–2018	self-reported estimates of work absenteeism and reductions in work performance caused by heat	Individual economic losses from heat stress related productivity losses estimated from productivity loss per daily average income per number of affected days	The median number of days in a year on which people felt their productivity had been compromised because of heat stress was 29. On those days half of the respondents felt their work capacity had been at least halved. The estimated median annual loss from reduced productivity was 257 €, nearly 10% of respondents' median annual income
Bonauto et al. 2007	descriptive study of compensation claim data related to heat	US Washington State	none	all work sectors (480 compensation claims for heat-related illness in the study period)	1995-2005	descriptive analysis of heat-related illness compensation claims and risk factors (outdoor/indoor, comorbidity, hours of the day, acclimatization)	A claim is assigned a ‘compensable’ claim status code if it involves 4 or more days of time loss from work. Both compensable and noncompensable claims were included in the study.	Median cost per compensable claim for heat-related illness was 1,916 US dollars. Median cost for non-compensable claim was $513.
Fortune 2013	descriptive study of heat-related injuries and compensation claim data	Ontario, Canada	none	all work sectors (612 compensation claims for heat-related illness in the study period)	2004-2010	Incidence rates calculated using denominator estimates from national labour market surveys and estimates were adjusted for workers’ compensation insurance coverage. Proportional morbidity ratios were estimated for industry, occupation and tenure of employment	lost time claims	incidence of heat illness is highest in the June to August period. A total of 40% of all heat illnesses were clustered in epidemics over contiguous days. The rates of lost time claims were highest among workers aged 15-24, males, and among Manufacturing (25%), Government Service (15%), Construction (10%) and self-insured public sector employers (10%) sectors.
Hesketh 2020	descriptive study of heat related injuries	US Washington State	maximum daily and 3-days temperature (°F) > 89°F (threshold to protect workers)	645 heat related injuries occurred in all work sectors	2006-2017	descriptive analysis of time losses and costs per injury	work time loss due to heat related injuries. Claim costs (in US dollars) for compensable and non compensable (medical aid only) claims, excluding indirect costs to employers and workers and the administrative costs of managing the claim.	Median time loss 13 work days related to heat injury. Higher costs of heat related injuries than for the total injuries (909 US dollars and 800 US dollars respectively), for both compensable and non compensable claims.
Ma et al. 2019	time-series study on heat-related injuries	China	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors	2011-2012	Time series study to examine the association between heat stress (WBGT values) and insurance payouts for work related injuries	The daily insurance payouts calculated by aggregating amounts of individual payouts, and also showed as US dollars	4.1% of insurance payout was attributable to heat stress (all days in the study period with WBGT>25°C), corresponding to 11.58 million Chinese Yuan. Stronger associations in female workers, workers employed in medium-sized enterprises, and workers with intermediate education level
Martínez-Solanas et al., 2018	time-series study on heat-related injuries	Spain	Extreme cold and heat defined as temperatures below the 2.5 th and above	occupational injuries in specific economic sectors for investigation	1994–2013 (both heat and cold)	Time series study between daily maximum temperature and the daily count of occupational injuries causing at least one day	Costs estimated based on a previous study in 2007-2008 estimating a) costs associated with maintaining production	€319.39 million annually related to heat (297.82 moderate heat, 21.57 extreme heat). Annual costs related to moderate and extreme heat from pain and suffering: 182.97€, maintaining production:59.21€,

Reference	Study type	Country	Heat exposure	Study population	Study period and duration	Cost calculation	Economic loss estimation (unit measure)	Results
			the 97.5th percentiles, and moderate heat and cold between minimum mortality temperature and the extreme thershold respectively	based on previous research (Xiang et al. 2014a; Adam-Poupart et al. 2015) (no information about indoor and outdoor)		of leave. Economic analyses based on a previous study on the costs of occupational injuries in the Catalonia region (Abiuso and Serra2008)	(including overtime payments and costs of replacement and training), b) longterm lost incomes (total income lost when a worker suffers an injury and cannot come back to work), c) health costs associated with costs of treatment and rehabilitation, and d) costs of pain and suffering (level of disability).	longterm lost incomes: 49.16€, and health costs: 28.06€.
Rameezdeen and Elmualim (2017)	case-crossover study of heat-related injuries	Adelaide, Australia	Heat wave: five or more consecutive days of maximum temperature in excess of 35°C or three or more consecutive days of temperature in excess of 40°C	construction sector (29,438 compensation claims during the study period)	heat waves 2000-2010	analysis of the impact of heat waves on occurrence and severity of construction accidents. Compensation claims recorded during the heat wave periods were compared with those during similar “control periods”.	Compensation claims and costs (australian dollars)	Worker characteristics, type of work, work environment, and agency of accident increase the risk of severe compensation claim during heat waves. Small companies had a proportionately higher share of severe injuries. Mean cost of injury was higher in central part of Adelaide, and in small campanies and for specific agencies of accident (structure, electricity, environment, small tool, and vehicle).
Spector 2014	descriptive study of heat-related illness	Washington, US	Maximum and minimum temperature and temperature range, heat index	agriculture and forestry sector (84 heat-related claims in the study period)	1995-2009	Analysis of determinans of heat-related compensation claims	Cost per compensation claim (US dollars). Time-loss days per claim (days)	Comorbidity and drug use increase risk of heat-related claim. The mean cost per heat-related claim was 3502 US dollars and 3071 US dollars for total and non-compensable claims respectively. Costs were several times lower than average cost of all claims. Severe heat-related claims mean cost was 24,533 US dollars. Mean number of time-loss days was 25 (0-96) days.
Xiang 2018	time-series study on heat-related workers compensation claim data for injuries	South Australia	Maximum temperature	all work sectors (438 heat related occupational injuries in the study period)	2000-2014	Medical costs related to injuries	Costs (Australian dollars) Day lost due to injury	A 1 °C increase in Tmax above about 33 8C was associated with a 41.6% increase in medical costs and a 74.8% increase in days lost due to OHI, respectively

Table 2. Results of economic studies estimating productivity, social or economic losses related to occupational heat exposure present and future at regional and global level.

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
Global studies							
Burke 2015	global level, rich and poor countries, by country	annual mean temperature	several occupation types	2050-2100 compared to 1960-2010 (two socioeconomic scenario consistent with RCP 8.5)	non linear analysis between global and country economic production and temperature	productivity of industries non of individuals (change in GDP per capita)	climate change reduces projected global GDP by 23% in 2100 (best estimate, SSP5) relative to a world without climate change. Reductions are similar in rich and poor countries, while are larger in countries becoming warmer
Chavaillaz et al. 2019	global level (high and low income countries) and by country	Wet-bulb Globe Temperature (WBGT) index of heat stress	vulnerable industries to heat exposure (agriculture, mining and quarrying, manufacturing and construction workers)	different emission scenarios (1% CO2, RCP4.5 and RCP8.5) compared to the pre-industrial period (1861–1880)	analysis between CO_2 and other greenhouse gases emissions (predictor of mean temperature increase) and GDP losses	The change in mean number of annual hours employees lost in vulnerable occupational sectors due to the increase in heat exposure, expressed as % of GDP	The relationship between productivity loss and CO2 emissions is robustly linear at global scale. For each trillion tonne of carbon emitted, the annual productivity loss will globally increase by 1.84% (±0.94, 1σ-intervals due to climate and inter-model variability), 2.96% (±1.97) and 3.61% (±1.77) of total GDP in the 1% CO2, RCP4.5 and RCP8.5 scenarios, respectively. Some high-middle income countries are subject to the highest impacts; for example, Gabon, India, Thailand and Malaysia all experience productivity losses from 3 to 5% of total GDP per year for every TtC emitted. non-CO2 gases contribution seemed larger than that of CO_2 alone.
DARA 2012 grey literature	global and country level	annual mean temperature	several occupation types	2010-2100 scenarios	analysis of labour productivity losses from international labour standards and estimates of wet bulb globe temperature (WBGT) change for populations assumed to be acclimatized. The model accounts for productivity gains to countries in high latitudes that will experience a reduction in extreme cold.	loss of labour productivity is calculated for both indoor and outdoor workers and expressed in USD	These results projected a total global GDP loss of US$2.5 trillion (PPP $) per year for 2030 (1% loss of global GDP in 2030, 0.5% loss in 2010). As a percentage of the national GDP, losses varied markedly and were greatest in tropical low- or middle-income countries (e.g., 0.0% in the United Kingdom and Japan, 0.2% in the United States, 0.8% in China, 3.2% in India, 6.0% in Indonesia and Thailand, and 6.4% in Nigeria and Ghana)
Dasgupta 2021	global and regional level	mean temperature and wet-bulb globe temperature (WBGT).	low-exposure working conditions (labour outside in the shade or indoors—eg, manufacturing) and high-exposure working conditions	1·5°C, 2·0°C, and 3·0°C of global warming compared with the historical baseline period (1986–2005)	the effect of climate change on labour productivity using five different exposure-response estimated from literature	Change in Effective Labour=(100% + Change in Labour Supply) * Change in Labour Productivity	Europe is expected to be the least affected region, while the highest impact will be in Sub-Saharan Africa

Reference	**Country**	**Heat exposure**	**Work sectors**	**Study period**	**Cost calculation**	**Economic loss unit measure**	**Results**
			(outside with no shade—eg, agriculture and construction)				
De Lima 2021	global and regional level	ESI and sWBGT	agricolture	1·5°C, 2·0°C, and 3·0°C of global warming compared with the 1986–2005 baseline	1) National Institute for Occupational Safety and Health (NIOSH) labor standards for agricultural workers (400 W) [29, 48], and an associated function for labor capacity 2) Dunne algorithm to estimate labour capacity	Change of unskilled employment in agriculture accounting for impacts in crop yields	In sub-Saharan Africa and Southeast Asia heat stress with 3°C global warming could reduce labor capacity in agriculture by 30%–50%, increasing food prices and requiring much higher levels of employment in the farm sector
Dunne et al. 2013	global level	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor workers	Reanalysis 1971–1980 and 2001–2010, projected 2091–2100 and 2191–2200	analysis focused on the loss of labor productivity as a function of WBGT levels during the hottest months in each part of the world over the period 1975–2200 under high emissions (RCP 8.5) and mitigation (RCP 4.5) scenarios	Population-weighted individual labour capacity (%) during annual mimimum and maximum heat stress months estimated from WBGT applied to US national and international standards for safe work intensities (90% means 10% losses in labour capacity)	Reductions in work capacity during the hottest months already occur at the global level (10% reduction). By 2050 under both scenarios, work capacity loss is two-fold higher than in the historical period (20% reduction). By 2100, the reductions in the hottest month may reach 37% based on RCP8.5 and 20% based on RCP4.5. By 2200, very significant further changes in work capacity are projected for the hottest month based on RCP8.5 (61% reduction), and 12% of population is exposed to work capacity losses
Kjellstrom et al. 2009	global level 21 geographic regions	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (service, industry, and agriculture) both indoor and outdoor	2020, 2050 and 2080 compared to 1961–1990	Projections of future labor productivity losses (in terms of lost labor days) under climate scenarios A2 (worst) and B2 compared to baseline climate applying dose-response function between WBGT and work capacity estimated in Kjellstrom et al. 2009b	The change in labor productivity is expressed as percent work days lost and incremental change relative to baseline	By the 2080s, the greatest absolute losses of population based labor work capacity (in the range 11% to 27%) are seen under the A2 scenario in Southeast Asia, Andean and Central America, and the Caribbean. Under B2 scenario smaller impacts in all regions (the greatest loss being 16% in Central America), and labor productivity gains in some regions (up to 6%)
Kjellstrom T 2015	21 global regions	Wet-bulb Globe Temperature (WBGT) index of heat stress (calculated using Hothaps functions)	all work sectors (outdoor and indoor)	2030 and 2050 versus 1960-1989	lost work capacity calculated using exposure–response relationships from literature	Cost of labor productivity loss due to excessive heat, % of GDP	for South-East Asia the new estimates (taking workforce changes into account) indicate work capacity losses increasing from 17% to 29% (of daylight work hours) from 1975 to 2050 for outdoor workers doing heavy labor. The corresponding figures for indoor workers doing heavy labor are 3% to 8%, and for outdoor workers doing moderate labor the estimates go from 7% to 15%. Low- and middle-income countries have higher losses 6% of annual GDP compared to high income countries. The estimated annual losses, expressed as $US PPP, are already in 2010 up to 55 billion (India) and in 2030 up to 450 billion (India and China)

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
Kjellstrom T 2016 grey	global and regional level	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (service, industry, and agriculture) both indoor (or shade) and outdoor (or sun)	30-year periods around 1995 and 2085 at different global warming levels between 1.5 ºC (RCP2.6) and 4 ºC (RCP8.5)	Lost work hours are calculated based on the geographic distribution of adult (working age) population numbers for the year 2000, and expressed as the annual percent of daylight hours lost due to heat	annual percent of daylight hours lost due to heat at 300W. The percentages refer to potential annual daylight hours when health and productivity problems due to heat start occurring for moderate work and labour productivity falls as workers slow down or take more rest	Now, it is so hot that productivity is lost up to 10-15% of annual daylight hour. There is a 10-times or more increase of work hours lost from 2015 to 2085 for a number of countries under RCP8.5 scenario. The worst impacts are estimated for Asia and the Pacific region with similar impacts also in West Africa. Latin America and the Caribbean have lower impacts and in Europe some impacts occur in the South. By the end of the century this will increase in the hottest areas even if . temperatures are held at 1.5 ºC (RCP2.6), but the increase is much higher for the business-as-usual scenario of 4 ºC (RCP8.5), reaching more than 30%
Kjellstrom T 2018	global and regional level	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (service, industry, and agriculture) both indoor (or shade) and outdoor (or sun)	2011–2040, 2041–2070, and 2071–2099 versus 1981–2010 (RCP2.6 and RCP6.0 scenarios)	risk functions from epidemiological studies were used to convert an environmental heat level (expressed as WBGT) directly into a Bproductivity loss^ (percentage of reduced work capacity) if the worker reduces work intensity to avoid clinical health problems	percent of work hours lost (at moderata work intensity levels,300 W metabolic rate in the shade) relating the calculated numbers to the total potential person-hours of work in that area	Under the more extreme climate change trend (RCP6.0; GTC increase of 2.7 °C), as much as 12–16% of annual work hours will be lost in some areas. Countries with large cool climate areas (such as USA) have limited work hour losses due to heat now (0.17%), but it may increase beyond 1.3% at the end of the century based on the current global climate policy pathway (RCP6.0)
Kjellstorm et al.,2019a grey (ILO report)	global level	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (agriculture, construction, industry, services)	2030 and 2085 compared to 1995 (1981-2010) under RCP6.0 (worst) vs RCP2.6	Projections of future labor productivity losses (in terms of lost labor days) by combining a global temperature rise of 1.5°C by the end of the twenty-first century with labour force trends compared to baseline climate, applying dose-response function between WBGT and work capacity estimated in literature for moderate and heavy labor.	estimated annual labor productivity losses, expressed as $US PPP (or % of GDP) or equivalent full time jobs due to excessive heat by country	By 2030 the share of total working hours lost will rise to 2.2 per cent – a productivity loss equivalent to 80 million full-time jobs. The loss in monetary terms is then expected to total US$2,400 billion (PPP). Lower-middle- and low-income countries would be the worst affected, losing 4 and 1.5 per cent of their GDP in 2030, respectively.
Knittel 2020	global level	Wet Bulb Globe Temperature	heavy outdoor work (agriculture, construction)	2036-2065 (RCP4.5 and RCP8.5) vs 1981–2010	GCM projections of the annual WGBT cycle and corresponding work ability and relative changes for heavy outdoor work are calculated. To derive work ability values, the exposure-response relationships between WBGT and work ability from literature were applied	relative change in work ability (%)	By 2050, within Europe, reductions are most pronounced for Italy and other Mediterranean countries (Cyprus, Greece, Malta, Portugal, Spain), while other countries are only marginally affected. Other world regions are severely impacted such as Southeast Asian countries, India and oil exporting countries. In the Amazon region, heavy outdoor work (400W) is projected to decline by more than 50% under RCP8.5.

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
Kuhla 2021	global and regional level	daily mean temperature	agriculture, fishing, mining and quarrying, hotels and restaurants, wholesale trade, and others	2020-2039 versus 2000–2019 (RCP2.6 and RCP6.0 scenarios)	Perturbed productivity is calculated based on the daily mean temperature surpasses 27˚C suffers a linear reduction αs in its productivity with beta coefficient sector-specific. Absolute output losses are then determined by multiplying the perturbed productivity with the baseline production of that region	Absolute and relative heat stress-induced direct output losses	Globally, between 2000 and 2039 direct output losses increase by 47% if no further adaptation measures are taken. Regional increase in direct losses in the billions USD (e.g. in India, Saudi Arabia, or Mexico) or nearly double the direct output losses (e.g. in Northern America or Europe) within the next decades.
Lancet Countdown 2021 (Romanello 2022)	global and country level	Wet Bulb Globe Temperature	agricultural, construction, manufacturing and service sector workers	1990-2020 (annual estimates)	hours of work lost calculated by linking Wet Bulb Globe Temperature with the amount of energy typically expended by workers in four sectors: agriculture, construction, service, and industry. It then combines this calculation with the proportion of people working (over 15 years old) in each country.	potential hours of labour lost due to exposure to heat by labour sector (in millions)	295 billion hours of potential work were lost due to extreme heat exposure in 2020, with 79% of all losses in countries with a low Human Development Index occurring in the agricultural sector. Conservative estimates since shade work is considered.
Lemke, unpublished observations (in Kjellstrom 2016 review)	global and country level	Wet-bulb Globe Temperature (WBGT) index of heat stress	workers outdoor in the shade and indoor (no cooling) for moderate work	2085 (2070–2099) under RCP scenarios 8.5 (worst) and 2.6 compared to 1995 (1980– 2009)	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose-response function between WBGT and work capacity estimated in literature for moderate labor	person-hours lost due to heat in whole regions (i.e., the work capacity loss multiplied by the working population in each grid cell and then summed up for all grid cells in a region)	The substantial reduction in work capacity (and related labor productivity) between 1995 and 2085. The areas with the greatest risk in 2085 remain the same (Amazon region, West Africa, Arab Gulf area, Pakistan, North India, Indonesia, and parts of China), but substantial reductions in work capacity are apparent in the southeast United States, parts of Europe, Africa, and the rest of India and China
Matsumoto 2021	global and country level	Wet-bulb Globe Temperature (WBGT) index of heat stress	agriculture, manufacturing, and service	2100 vs 2007 (business as usual scenario)	climate change impact on labor productivity (the relationship between heat stress measured by wet bulb globe temperature [WBGT] and labor productivity).	labour productivity reductions (%)	the impacts were the largest for the agricultural (36.8–100% labor productivity by 2100), and 238 the lowest for the service sectors (83.0–100% productivity by 2100).
Orlov et al., 2020	global	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors agriculture and construction are assumed to be high-intensity jobs (400 W), while manufacturing and services require	2020, 2030, 2040, 2050, 2060, 2070, 2080 and 2090 compared to 1981-2005 under RCP8.5 (worst) and 2.6 scenarios	Productivity loss estimated using the Hothaps exposure-response functions or ISO functions, and the associated economic costs are assessed by using a dynamic multi-region, multi-sector computable general equilibrium model	GDP from labor productivity loss, estimated by decreased work efficiency	Heat stress leads to substantial reductions in worker productivity, especially of high intensity work in low-latitude countries of Africa, South America, and Asia. Given the assumption of absence of ACir conditioning and constant work intensity, reductions in worker productivity in some regions under RCP8.5 could even exceed 40% by 2100 compared to the reference. Agriculture and construction are the most adversely affected by heat stress.

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
			moderate-intensity (300 W) and low-intensity work (200 W),				
Parsons 2021	global and country level	sWBGT	all work sectors	2001-2020	calculation of the maximum work loss in the 12-hours work day on the basis of exposure-response functions from literature	Heavy labour lost (hours) Productivity loss (Billions PPP US dollars)	Current global estimates of productivity losses are 670 billions PPP US dollars in the 12-hours work day. Under +2°C warmer world, productivity losses reach 1.6 trillion PPP US dollars.
Parsons 2022	global and country level	sWBGT	outdoor workers in heavy labor sectors (agriculture, forestry and fisheries; construction)	2001-2020	calculation of the maximum work loss in the 12-hours work day on the basis of exposure-response functions from literature	Heavy labour lost (hours) Productivity loss (Billions PPP US dollars)	Global labor losses higher estimates are 2.1 trillion PPP US dollars. China and India again experiencing the largest losses, and Indonesia and the United States showing over 90 billion PPP$ losses per year. India experiences annual productivity losses equivalent to almost 7% of its 2017 GDP.
Roson et al., 2016 (Roson and Sartori, 2016)	global and regional level	Wet-bulb Globe Temperature (WBGT) index of heat stress	agriculture, manufacturing, service	scenarios of 1, 2, 3, 4 and 5 °C increases in average temperature (study period not specified)	projection of loss in labor productivity from relationships between average temperature and labor productivity under scenarios of 1, 2, 3, 4 and 5 °C increases in average temperature (study period not specified)	GDP from labor productivity loss, estimated by lost hourly worktime	Agriculture is the sector most significantly affected by higher heat stress. Some effects are felt by about half of the countries already at +1°C. The mean productivity losses range from -2.52% to -17.48%
Takakura et al., 2017	global	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (outdoor and indoor and different intensity)	2100 under four representative concentration pathways (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) compared to baseline (2005)	projection of loss in labor productivity from relationships between WBGT and labor productivity under scenarios of increase in WBGT	yearly average worktime reduction based on the recommendation of work/rest ratio and the estimated future wet bulb glove temperature and GDP losses (cost of heat-related illness prevention through worker breaks)	Under the highest emission scenario, GDP losses in 2100 will range from 2.6 to 4.0% compared to the current climate conditions. The relationship between the cost of heat-related illness prevention through worker breaks and global average temperature rise is approximately linear
Regional studies							
Altinsoy 2014	western Turkey	daily maximum WBGT	agricolture and construction	1971-2000 (baseline) 2011-2040, 2041-2070, 2071-2100 (scenario A1B - one of the highest emissions scenario) Only Spring,	Labour productivity losses (work hours) calculated assuming a specific rest/work ratio varying from 25%-50%-75%-100% (15-30-45-60 minutes rest for 1 work hour) every time that WBGT exceeds a specific threshold of 27.5°C, 29.5°C, 31.5°C and 36°C for heavy work intensity.	Work days lost	The most important productivity decreases are expected in the summer. The main impact on work productivity becomes evident after 2040. In Turkey decrease in labour productivity losses in agricolture vary from 1% (baseline), to 2% in 2011-2040, 5% in 2041-2070 and 8% in 2071-2100. In some areas the largest decrease reaches 52%.

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
				Summer, Autumn seasons.	Decrease calculated as percentage of total number of days in season. Expected decline in labour productivity is multiplied with the agricolture contribution to the economy to yield the total decline in labour productivity in agriculture.		
Amnuaylojaroen, T. 2022	5 megacities in Thailand	Steadman Heat Index	not specified	1990-1999 (baseline), 2020 and 2029 RCP 8.5 (very high emissions)	Labour productivity losses (work hours) calculated from the following formula: 2 x heat index - 50 based on experimental data	Percent decrease in labour productivity (%)	A widespread increase of heat index in the country and related decrement in labour productivity between 4 and >10%
Behrer 2017 grey	US	production-relevant temperature stress, TE, as a measure of extreme heat	non agricoltural sectors	1986-2011 and climate change scenarios in 2040-2050 (under RCP 4.5)	panel regression of payroll and maximum temperature by county and year	payroll per capita (close proxies to changes in total and marginal labor product)	Average U.S. county experiences a -0.04% reduction in payroll per capita during a year with one additional day with maximum temperatures above 95°F (35°C). The impacts are roughly 9 times as large in exposed sectors (construction, transportation, utilities, manufacturing, and mining). For instance, lost payroll under a no adaptation scenario is at least 50% higher in 2040-2050 compared a scenario in which local economies adapt to their new (hotter) climates.
Costa and Floater 2015 grey literature	3 EU cities Antwerp (Belgium), Bilbao (Spain), and London (United Kingdom)	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors	2026 – 2045 and 2081–2100 scenarios compared to a reference period (1986 – 2005) (under RCP 8.5)	analysis of sectoral production as a function of WBGT, sector-specific capital and labour	Annual labor productivity loss, estimated by lost hourly worktime, and expressed as % of Gross Value Added (GVA) at the sector level	Productivity (annual GVA) loss of 0.4% in London ($2111 million), 2.1% in Antwerp ($2778 million) and 9.5% in Bilbao ($777 million) projected in 2081–2100. GVA was observed to monotonically decrease with increasing WBGT.
deBoer 2021 (TNC 2021)	Phoenix area (US)	number of days over 110°F	all work sectors	2020-2039 and 2040-2059 vs 1986-2005 (RCP 4.5 and RCP 8.5)	productivity loss estimated as a function of temperature increases under climate change	Losses to Gross Regional Product (GRP)	Labour productivity losses are $855 and $964 million US dollars in 2020-2039 and 2040-2059 respectively
Deloitte 2020 Grey	Australia	annual mean temperature	all work sectors	global average warming of above 3°C by 2070 under RCP 8.5	Employment figures reported are reflective of the total headcount of employee jobs lost – both part-time and full-time equivalents. The ratio for conversion of full-time equivalents (FTE) (modelled by DAE-CLIMATE) to total headcount has used an FTE ratio based on 2016 Census data.	Economic losses due to job losses caused by climate change, as % of GDP or US dollars	the economic losses to Australia from unmitigated climate change are $3.4 trillion in present value terms – or 6% of GDP by 2070. On average over the 30 years to 2050, that is a loss of 135,000 jobs per year and 1.8% of GDP. the worst impacted industries are service sectors (both government and business), trade and tourism, manufacturing, and mining
Heal & Park 2013	US and other countries	annual mean temperature	all work sectors	1950-2005	linear regression between GDP and temperature taking into	effective labor supply – defined as a composite	Very hot countries such as Thailand, India, and Nigeria suffer negative output shocks on the order

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
					account of the following: 1) Each country's annual per capita GDP is produced using a combination of capital and effective labor input. 2) Effective labor input defined as a composite of labor hours, labor effort, and labor performance is a function of the ambient temperature. We allow for the possibility that temperature may affect GDP with a time lag, by allowing for 1, 5, and 10 lags. For the US, household data on air conditioning and heating expenditures	of labor hours, task performance, and effort	of 3-4% per capita GDP per degree Celsius. Very cold countries such as the UK, Canada, Norway, and Sweden have significantly higher output in warmer years (and lower output in colder years). In the US, A household with an average age of 20 spends roughly 15% ($28) more per year on AC and 12% ($54) less on heating than an otherwise equivalent household with an average age of 60 and expenditure on both AC and heating are higher for households with someone at home who is working than for those with someone at home but not working
Hsiang 2010	Carribean and Central America	annual mean temperature	different work sectors	1970-2006	economic responses to annual average temperature driven by performance losses	change in production due to temperature increases (% change for 1°C increase)	Wholesale, retail, restaurants and hotels (-6.1% per 1 °C increase), and other services (-2.2% per 1°C increase) exhibit significant production losses
Hübler et al., 2008	Germany	perceived temperature (Jendritzky et al. 2000)	all work sectors	2071-2100 compared to 2004	Assuming that heat directly reduces productivity, predictions of GDP losses for future temperature scenarios by applying a reduction of 3% to 12% under strong or extreme heat stress estimated by Bux (2006)	Average GDP loss per year in Germany in the prediction period 2071–2100 for IPCC scenario A1B	Considering the worst scenario (A1B), future (2071-2100) losses are 2.5 billion $ (0.12% of GDP) or 10.4 billion $ (0.48% of GDP) with labor productivity loss of 3% and 12% for strong and extreme heat, respectively. Actual losses are 540 million € and 2.4 billion € with labor productivity loss of 3% and 12% for strong and extreme heat, respectively.
Kershaw 2013	UK	predicted mean vote	indoor work sectors	2030s, 2050s and 2080s under A1F1 scenario versus 1970s	the cost of lost productivity per m2 as a result of thermal discomfort over the year. The productivity per worker within a given sector can be calculated by dividing the GVA for that sector by the number of people employed in that sector measured as Full Time Equivalents (FTE). The change in relative productivity as a function of user comfort can be applied to the economic output of a worker. A typical office building is used.	cost per m2 of office building (pounds)	as the climate warms then the cost of lost productivity increases from 134 pounds per square meter in 1970s to 148, 164 and 181 pounds per square meter in 2030, 2050 and 2080 respectively
Kjellstrom et al. 2009b	Delhi (india)	WBGT	outdoor work in the sun	May 1999	model effect of the heat exposure on work capacity	remaining 500 W Work Capacity at each hour (%)	work capacity for a person who works at a heavy work intensity of 500 W is reducing during the day,

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
							with on average only 20% of work capacity remains at 12 noon
Kjellstrom T 2013	Southeast Asia	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors both indoor (or shade) and outdoor (or sun), for heavy and moderate work	1975 (1961-1990) and 2050	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose-response function between WBGT and work capacity estimated in literature for moderate (300 W) and heavy labor (400 W)	Percent of total work time loss due to rest and slower work due to heat for moderate and heavy labor	in 1975 in the hottest locations 30-40% of afternoon work time is lost in the shade and 60-70% lost in the sun. In 2050 in hottest areas afternoon worktime is lost due to heat up to 80% for heavy work and up to 50% for moderate work
Kopp, 2014 Grey literature	US	daily maximum temperature	all work sectors	2020-2039, 2040-2059, 2080-2099 scenarios compared to 2012 climate (RCP 2.6, 4.5, 8.5)	Projections of changes in labor supply under different climate scenarios relative to a future in which the climate does not change after 2012 using the dose-response functions obtained by Graff Zivin and Neidell (relationship between maximum temperature on the number of minutes individuals work from survey data). The dose-response functions accounted for cross-county patterns in labor markets, as well as trends over time and over seasons	Labor Productivity as minutes worked for high-risk (agriculture, construction, utilities, and manufacturing) and low-risk labor sectors	In RCP 8.5, high-risk labor likely declines by 0.2% to 0.9% by 2040-2059 and by 0.8% to 2.4% by 2080-2099. For low risk labor supply, losses are more modest, with 2080-2099 losses in RCP 8.5 of 0.1% to 0.5%, with a 1-in-20 chance that labor supply falls more than 0.8% or less than 0.01%. Projected changes are smaller in magnitude for RCP 4.5 and RCP 2.6.
Kovats et al., 2011 grey Grey literature	Europe	Wet-bulb Globe Temperature (WBGT) index of heat stress	all work sectors (agriculture, industry, and service)	2020, 2050, 2080 under SRES A1B (medium–high emission) and E1 scenarios (mitigation scenario) compared to 1961-1990	Projections of future labor productivity losses (in terms of lost labor days) by combining a global temperature rise of 1.5°C by the end of the twenty-first century with labour force trends compared to baseline climate, applying dose-response function between WBGT and work capacity estimated in literature by work intensity. The model account for future labour productivity split in Europe.	Loss of labour productivity, derived from the GDP per labour force member using EU27 average productivity cost value of €287 per day.	Under the current climate, the only impacts are in Southern Europe, where losses were estimated to be 0.14% days lost. Higher impacts are projected for Mediterranean countries with climate change. Under A1B scenario, for Southern Europe a 0-4-0.9% loss in productive days by the 2080s. Total productivity losses (whole European area) are estimated at €120 - 320 million/ in the 2050s, rising to €300 - 740 million/ in the 2080s under A1B scenario.
Lee 2018	South Korea	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor laborers	2011-2040, 2041-2070, 2071-2100 compared to 1981–2005 summer season (June to September) under	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose-response function between WBGT and work capacity	outdoor labor productivity loss by intensity (moderate and heavy work)	For moderate work productivity losses by 4.8% and 15.8% by 2071-2100 under RCPs 4.5 and 8.5, respectively, compared to the current level of 99.9%. Productivity losses for heavy work are 12% (RCP4.5) and 26.1% (RCP8.5). Areas with larger

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
				RCP 8.5(worst) and 4.5	estimated in literature for moderate and heavy labor.		productivity losses are those with higher proportion of outdoor workers.
Licker 2022	US	maximum heat index	outdoor workers (included agriculture, construction and transportation)	2036–2065 and 2070–2099, versus 1971–2000 (RCP4.5 and RCP 8.5)	Heat-based work reduction recommendations were accounted for an analysis of hourly weather station data to develop novel algorithms for calculating the annual number of unsafe workdays due to extreme heat	Annual earnings (Billions USD) at risk (%) for moderate and light workload	the average outdoor worker in the United States risks losing approximately $1,200 in earnings per year under RCP4.5 and approximately $1,700 per year under RCP8.5. In terms of absolute dollar values, at mid-century under RCP8.5, total potential losses are highest for construction and extraction occupations.
Liu 2020	China	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor workers	near future (2021–2050) and the end of the century (2071–2099) under RCP scenarios 8.5 (worst) and 2.6 compared to baseline (1981–2010) (July and August)	Projections of future labor productivity losses (in terms of lost labor days) compared to baseline climate, applying dose-response function between WBGT and work capacity estimated in literature for light, moderate and heavy labor	Changes in labor capacity are then estimated for light, moderate and heavy work	Large decreases (more than 40%) in labor capacity of heavy work due to increased WBGT were found for many areas of China in the future, especially at the end of the century under RCP8.5. In South and East China, labor capacity of light work would also experience a significant decrease (by 40% to 50%) under the high emission scenario.
Martinich 2019	US	as specified in Graff Zivin, J. and M. Neidell 2014	as specified in Graff Zivin, J. and M. Neidell 2014	RCP 4.5 and RCP8.5 in 2050 and 2090 vs 2003-2007	Lost labor supply hours due to changes in hot and cold temperature, including extreme temperatures [E]	Lost Labor Hours (millions) and Lost wages (US dollars) in high-risk industries from the 2003–2007 reference period, normalized by the high-risk working population by county	44,000 US dollars in terms of wages lost in 2050 and 160,000 US dollars wages lost in 2090 under RCP8.5
Orlov et al., 2019	10 European countries	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor workers (agriculture and construction)	heat waves August 2003, July 2010, and July 2015	to calculate direct economic losses, the sectorial value-added by relative reductions in worker productivity. Also social costs were calculated by using a computable general equilibrium (CGE) model.	Productivity loss estimated using the Hothaps exposure-response functions and the ISO standards under high and moderate intensity work. To assess the direct economic losses (or direct private costs), we use the social accounting data	In August of 2003, the mean value of direct economic losses resulting from heat-induced reductions in worker productivity in the agricultural sector in the top ten most affected European countries accounted for approximately $83 per worker, whereas in July of 2010, it was $59 per worker, and in July of 2015, it was $90 per worker. With respect to the construction sector, the mean value of direct economic losses in August of 2003 amounted to $61 per worker, in July of 2010, it was $41 per worker, and in July of 2015, it was $72 per worker
Parks	US	day above 85°F	low and high risk sectors	1983-2016	the relationship between daily temperature and lost labor time when *T*emperature exceeds 85°F	total cost of lost labor (%)	In high-risk sectors, total cost of lost labor from 0.3% in 1983 to 0.58% in 2016
Rao 2020	India	Steadman Heat Index	not specified	1986-2005 (baseline) and 2016-2035, 2046-2065,	Labour productivity losses (work hours) calculated from the	Percent decrease in labour productivity (%)	he coastal regions of India (east and west coast) are found to be more vulnerable to heat stress impacts by showing a perceptible increase in the

Reference	**Country**	**Heat exposure**	**Work sectors**	**Study period**	**Cost calculation**	**Economic loss unit measure**	**Results**
				2080-2099 (RCP4.5 low emissions, RCP8.5 high emissions)	following formula: 2 x heat index - 50 based on experimental data		notorious impact days and a decline of 30 to 40% in the work performance, particularly in east coast region
Somanathan 2015 grey	India	Wet-bulb Globe Temperature (WBGT) index of heat stress	manufacturing industry	1971-2009	productivity estimated with different methods: from output data, from combined productivity of each line of workers. Absenteeism is also considered.	time series study of heat and productivity	Ambient temperatures have non-linear effects on worker productivity, with declines on hot days of 4 to 9 percent per degree rise in temperature. Sustained heat also increases absenteeism
Somanathan, E. 2021	India	Wet-bulb Globe Temperature (WBGT) index of heat stress	manufacturing industry	1998-2009	productivity estimated with different methods: from output data, from combined productivity of each line of workers. Absenteeism is also considered.	time series study of heat and productivity	the impact of a 1°C increase in temperature on district output was a declines of 3% per 1°C
Suzuki-Parker 2015	Tokio and Osaka (Japan)	Wet-bulb Globe Temperature (WBGT) index of heat stress	light and heavy labour work	2030s, 2050s, 2070s, and 2090s under A1B vs 2000	light labor hours and heavy labor hours refer to hours of WBGT below 30 and 25 °C, respectively	Hours losses (%)	Light labor hours are projected to decrease by 30–40 % by the end of the twenty-first century, while reductions reach 60–80 % for heavy labor hours
Szewczyk, W. 2021	Europe	Wet-bulb Globe Temperature (WBGT) index of heat stress	4 classes based on occupational vulnerability to heat stress	2020, 2050 and 2080 vs 1990s	Vulnerability and the impact functions determine workers' productivity losses from heat stress, and depend on type of work and its physical intensity.	Labour productivity change (%)	productivity of labour can be 1.6% lower in Europe in the worst case scenario. in 2080s, with a clear geographical gradient showing that southern and eastern regions are much more affected
Vivid Economy UK 2017	Ethiopia, Ghana, India, Jordan, Tanzania	Wet-bulb Globe Temperature (WBGT) index of heat stress	outdoor and indoor: agriculture, manufacturing, construction, other industry, wholesale and retail trade, transport, storage and communication, and other services.	2020 to 2039 and 2040 to 2059 vs 1986-2005	response functions reach a maximum productivity loss of between 86 per cent and 90 per cent at 38 degrees Celsius WBGT. labour response to increased temperatures follows the 'Hothaps' models	Total employment and 'equivalent effective workers' lost due to heat stress	These losses are 1-5% of productivity for a 1.5 °C temperature. In India the reduction is 20% of total workforce hours lost due to heat stress, the other countries losses are lower.
Xia et al., 2018	Nanjing, China	Humidex	all work sectors (indoor and outdoor)	14-days heat wave 2013	For manufacturing, energy supply and service sectors, who mostly work indoors a 12% reduction in productive working time was assumed (Bux 2006). For heat-induced work capacity loss due to workplace safety regulations, we assumed that	Industrial Reduced Productive Working Time and economic loss estimated from monetary value of sector outputs taking into account interdependencies between sectors	$3.88 billion, 3.43% of Nanjing's GVP in 2013. Most costs were indirect. Economic loss per industry: manufacturing: 63.1%, service: 14.3%, construction:10.7%, agriculture: 7.6%, energy supply: 3.3%, mining: 0.9%.

Reference	Country	Heat exposure	Work sectors	Study period	Cost calculation	Economic loss unit measure	Results
					excess heat only affects the work capacity of workers in the agricultural, mining and construction sectors, who mostly work outdoors with heavy work intensity and are directly exposed to heat. The reductions in industrial working time are summed and compared with the original industrial working time when there is no heat wave and thus no heat-induced health impact or productivity or capacity loss estimated the work capacity loss in terms of working time loss for outdoor workers using the Humidex		
Zhang 2021	US	Wet-bulb Globe Temperature (WBGT) index of heat stress	light, medium and heavy work	2050 and 2100 vs 1980-2016 (RCP8.5 and RCP4.5)	ERFs relating extreme temperature and labor losses based on WBGT	labour losses (billions US dollars) and losses as percentage of GDP (%)	Actual labour losses are $1.7 billion annually comparing 2006-2016 with 1980–1990. Whereas 2006–2016 losses correspond to 0.07% of the 2016 GDP, the 2100s losses rise roughly fourfold to 0.3%
Zhao 2016	China	high temperature days >35°C	all work sectors	2030, 2040, 2090 (RCP2.6, RCP4.5, RCP 8.5) vs 1979-2005	high-temperature subsidies (HTSs) are allocated to employees for each working day in extremely hot environments.	labour losses (billions Yuan) and losses as percentage of GDP (%)	the total cost of high temperature subsides in China is 38.6 billion yuan/y (US $6.22 billion/y) over the 1979–2005 period, 0.2% of the gross domestic product (GDP). Costs may reach 250 billion yuan/y in the 2030s and 1,000 billion yuan/y in 2100.
Zivin 2010	US	annual mean temperature	outdoor and indoor sectors	2003-06	ERFs relating extreme temperature and labor losses based on temperature	labour supply	For labor supply, there is little response to temperatures below 80 degrees, but monotonic declines in labor supply above 85 degrees. At temperatures over 100 degrees, labor supply drops by a statistically significant 59 minutes as compared to 76-80 degrees.

Supplementary material

Appendix 1. Search strategy

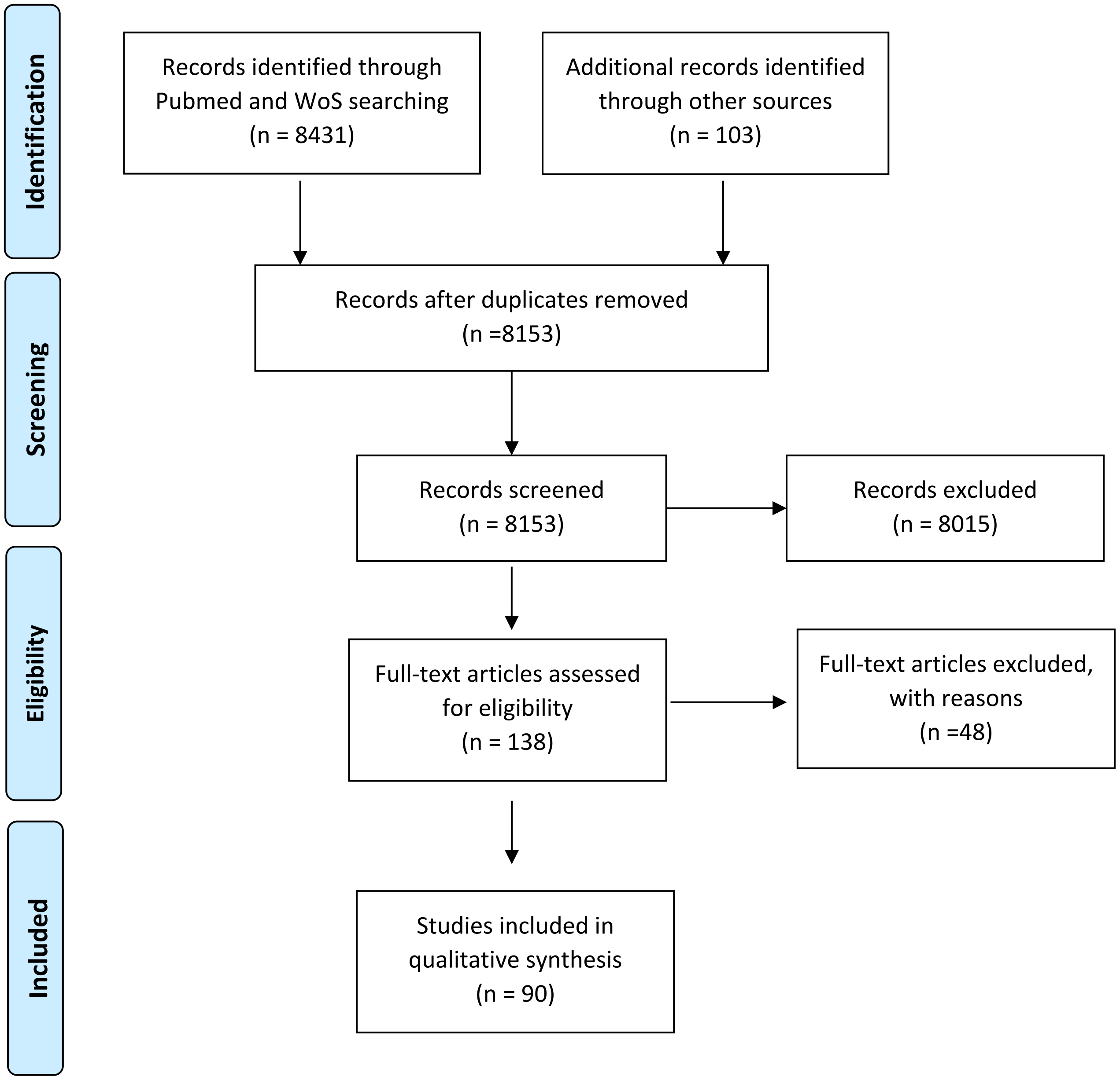
Appendix 2. PRISMA Flow diagram of studies selection.

Appendix 1. Search strategy

Database: Pubmed - Search launched in April 2022.	
Exposure (heat, high temperature, heatwave, climate change)	
#1	"Hot Temperature"[Mesh]
#2	(Heat[Title/Abstract] AND (exposure[Title/Abstract] OR stress[Title/Abstract] OR strain[Title/Abstract]))
#3	hot[Title/Abstract] AND weather[Title/Abstract]
#4	(hot[Title/Abstract] OR summer[Title/Abstract] OR high[Title/Abstract] OR extreme[Title/Abstract] OR ambient[Title/Abstract]) AND temperature*[Title/Abstract]
#5	heatwave*[Title/Abstract] OR WBGT[Title/Abstract]
#6	heat[Title/Abstract] AND wave*[Title/Abstract]
#7	climat*[Title/Abstract] AND (change*[Title/Abstract] or variat*[Title/Abstract])
#8	#1 or #2 or #3 or #4 or #5 or #6
Population (workers)	
#9	Work*[Title/Abstract] OR employ*[Title/Abstract] OR labour*[Title/Abstract] OR labor*[Title/Abstract] or occupation*[Title/Abstract] or job*[Title/Abstract]
#10	"Occupational Groups"[Mesh]
#11	#9 OR #10
Outcomes (costs, productivity, social impacts)	
#12	"Occupational Injuries/economics"[Mesh]
#13	"Cost of Illness"[Mesh]
#14	(impact*[Title/Abstract] OR burden[Title/Abstract] OR toll[Title/Abstract] OR benefit[Title/Abstract] OR gain*[Title/Abstract]) AND (Socio*[Title/Abstract] OR social*[Title/Abstract] societ*[Title/Abstract] OR economic*[Title/Abstract] OR economy[Title/Abstract])
#15	cost*[Title/Abstract]
#16	(sick*[Title/Abstract] OR disability[Title/Abstract] OR injury[Title/Abstract] OR accident[Title/Abstract]) AND (leave*[Title/Abstract] OR allowance[Title/Abstract] OR compensation[Title/Abstract])
#17	productiv*[Title/Abstract] OR efficiency[Title/Abstract] OR absenc*[Title/Abstract] OR absent*[Title/Abstract] OR loss*[Title/Abstract]
#18	"Absenteeism"[Mesh]
#19	"Efficiency"[Mesh]
#20	#12 or #13 or #14 or #15 or #16 or #17 or #18 or #19
#21	#8 AND #11 AND #20
#22	#21 AND "Humans"[Mesh]

Database: Web of science - Search launched in April 2022.	
Exposure (heat, high temperature, heatwave, climate change)	
#1	TI=(heat AND (exposure OR stress OR strain))
#2	AB=(heat AND (exposure OR stress OR strain))
#3	TI=(hot AND weather)
#4	AB=(hot AND weather)
#5	TI=((hot OR summer OR high OR extreme OR ambient) AND temperature*)
#6	AB=((hot OR summer OR high OR extreme OR ambient) AND temperature*)
#7	TI=(heatwave* or wbgt)
#8	AB=(heatwave* or wbgt)
#9	TI=(heat AND wave*)
#10	AB=(heat AND wave*)
#11	TI=(climat* AND (change* or variat))
#12	AB=climat* AND (change* or variat))
#13	#1 or #2 or #3 or #4 or #5 or #6 or #7 or #8 or #9 or #10 or #11 or #12
Population (workers)	
#14	TI=(Work* OR employ* OR labour* OR labor* or occupation* job*)
#15	AB=(Work* OR employ* OR labour* OR labor* or occupation* job*)
#16	#14 OR #15
Outcomes (costs, productivity, social impacts)	
	TI=((impact* OR burden OR toll OR benefit OR gain*) AND (Socio* OR social* OR societ* OR economic* OR economy))
	AB=((impact* OR burden OR toll OR benefit OR gain*) AND (Socio* OR social* OR societ* OR economic* OR economy))
	TI=(cost*)
	AB=(cost*)
	TI= ((sick* OR disability OR injury OR accident) AND (leave* OR allowance OR compensation))
	AB= ((sick* OR disability OR injury OR accident) AND (leave* OR allowance OR compensation))
	TI=(productiv* OR efficiency or absenc* OR absent* OR loss*)
	AB=(productiv* OR efficiency or absenc* OR absent* OR loss*)
	#12 or #13 or #14 or #15 or #16 or #17 or #18 or #19
	#8 AND #11 AND #20

Appendix 2. PRISMA Flow diagram of studies selection.



Source: Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71.